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Investigating the Magnetic Fields of High-Velocity Outflows from Active Galactic Nuclei

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MSc

**Thesis submitted for the degree of
Master of Science**



NATIONAL UNIVERSITY OF IRELAND, CORK

SCHOOL OF SCIENCE

DEPARTMENT OF PHYSICS

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I, Frederick Richardson, certify that this thesis is my own work and has not been submitted for another degree at University College Cork or elsewhere.

Frederick Richardson

Frederick Richardson

To everyone

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Abstract

The focus of my M.Sc. degree was the magnetic fields of the jets of Active Galactic Nuclei (AGNs). The exact mechanism for the high levels of collimation in AGN jets is poorly understood. Theoretical models suggest that the collimation of jets is at least partially the result of a helical magnetic field. The primary aim of this thesis is to search for evidence of this structure. For such a magnetic field it is expected to find a Faraday rotation measure gradient transverse to the jet, an increase in fractional polarisation towards the jet edges, and possibly a "spine-sheath" polarisation angle structure. AGN jets that feature more than one of these criteria mentioned may host helical magnetic fields.

Observations obtained in 2017 and 2019 of a sample of 16 AGNs (BL Lac objects) were analysed at four radio wavelengths: 6, 13, 17, and 21 cm. The data for these observations were obtained with the "Very Long Baseline Array" of ten radio telescopes spread across the United States. These were the first data of this kind for these AGNs. Observations at multiple radio wavelengths are needed to construct rotation measure maps and detect the presence of a helical or toroidal magnetic field.

Eleven of the 16 BL Lac objects host convincing transverse rotation measure gradients with statistical significances greater than 3σ . Two sources (J0738+1742 and J2202+4216) showed an increase in fractional polarisation towards both edges of the jet as well as a spine-sheath structure. In addition, J0748+2400, J0958+6533, J1800+7828, J1806+6949, J1824+5651, J2005+7752, and J2202+4216 had the EVPA and fractional polarisation structure discussed earlier which strengthens the argument for these jets possibly having helical fields.

A secondary objective of my research was to compare my results with the jet structures of these AGNs observed at four wavelengths between 18 and 22 cm at two earlier dates in 2004 and 2010. The morphology, polarisation structure outside the core, and fractional polarisation remained approximately constant. Analogous statistically significant Faraday rotation measure gradients were found at these earlier dates in J0050-0929, J1806+6949, and J1824+5651, and evidence for transverse RM gradient reversals was found for J0818+4222, J0825+0309, J1800+7828, and J2202+4216. The reversal of the direction of a transverse RM gradient with distance from the core or time could result from a nested helical field structure, with the toroidal components of the helical fields being in opposite directions in the inner and outer regions of helical field.

Chapter 1

Introduction

1.1 Active Galactic Nuclei

Unless stated otherwise, this section is based on material in the textbooks of Peterson (1997), Beckmann & Shrader (2012) and Burke & Graham-Smith (1996).

Generally, "active galactic nucleus", or AGN refers to the central regions of galaxies where the energy produced cannot be explained by stars and other thermal emission alone. AGNs typically output huge energy amounts, equivalent to up to several trillion stars in the volume of a cubic parsec. The first evidence that some galaxies were hosting some additional strongly emitting component in their centres was found by Carl Seyfert in the 1940s (Seyfert 1943), in the unusual spectra of six galaxies. Early studies noted emission lines in AGNs were very broad, upward of 1000 km s^{-1} . In addition, the centres of the emission lines did not correspond to the laboratory wavelengths of any known atomic species neither the hydrogen Balmer series nor any other common astronomical emission lines.

It is now known that AGNs are powered by a "central engine" consisting of a hot accretion disk surrounding a supermassive black hole. Energy is produced by the gravitational infall of matter, which is heated to extreme temperatures in the accretion disk. This process has the efficiency $\nu \approx 0.1$ which is an order of magnitude greater than that of hydrogen to helium fusion ($\nu \approx 0.007$) and leads to high luminosities. The deep gravitational potential of the black hole is the origin of the dynamical broadening. The issue of line identification also was solved upon the realisation that the extragalactic distances involved were of such magnitude that the cosmological expansion of the Universe redshifted known atomic emission lines to

their observed values.

Perpendicular to the accretion disk, an AGN jet can sometimes be observed. These highly collimated, bipolar outflows consist of material ejected from the centres of AGNs and can extend up to thousands of parsecs. The underlying physics of the launching and propagation of AGN jets is poorly understood and remains enigmatic.

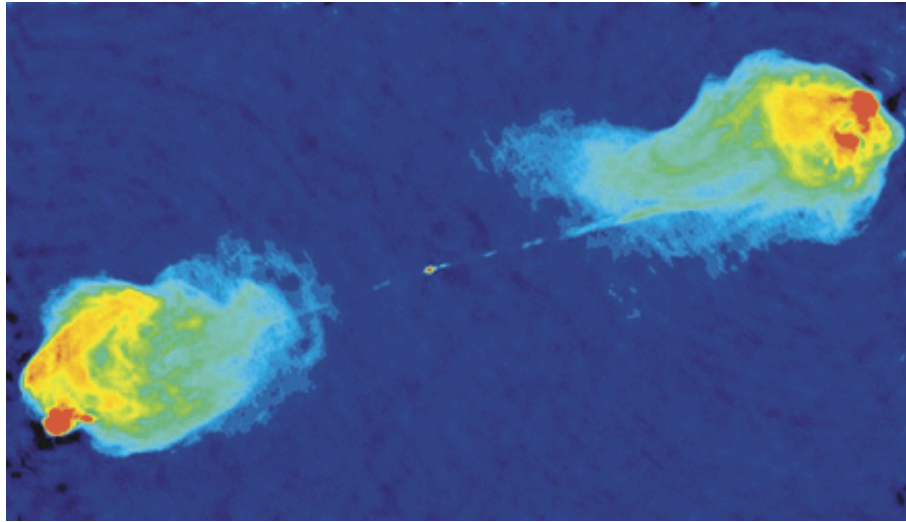


Figure 1.1: 6 cm false-colour image of the radio galaxy Cygnus A with showing narrow jets and hot spots. Image credit: NRAO/AUI; R. Perley, C. Carilli & J. Dreher

1.1.1 Taxonomy of AGNs

It is convenient to divide AGNs into two classes: radio-quiet and radio-loud AGNs. Radio-quiet AGNs, are typically 1,000 times fainter than the radio-loud AGNs at radio wavelengths but not at other parts of the EM spectrum. Radio-quiet AGNs represent the vast majority of the AGN population. Radio-loud objects have emission contributions from both the jet(s) and the lobes that the jets inflate. These emission contributions dominate the luminosity of the AGN at radio wavelengths and possibly at some or all other wavelengths. On the other hand, radio-quiet objects are simpler, since jet and any jet-related emission can be neglected at all wavelengths.

1.1.2 Radio-quiet AGNs

1.1.2.1 Seyfert Galaxies

First described in 1943 by Carl Seyfert, these were the earliest distinct class of AGN to be identified. They are low luminosity AGNs with a compact star-like nucleus but

have a clearly detectable host galaxy. Khachikian & Weedman (1974) were the first to divide Seyferts into two subclasses. The spectra of Type 1 Seyfert galaxies show both broad allowed lines such as like H I, He I, or He II and narrower forbidden lines, like O III, characteristic of low density ionized gas. In contrast, type 2 Seyferts have narrow spectral lines only. It has been suggested that all Seyfert 2s are intrinsically Seyfert 1s where the nucleus and broad-line emission is obscured from our point of view. It is unclear if this idea explains all of the perceived differences between the two subclasses.

1.1.2.2 LINERS

Low-ionization nuclear emission-line regions (LINERS) were first identified by Timothy Heckman in 1980 (Heckman 1980). LINER Galaxies exhibit very low nuclear luminosity and are very common, possibly existing in half of all spiral galaxies. They only show a weak nuclear emission-line region with no other signatures of AGN emission. It is debatable if LINERS are even truly AGNs and some argue they are not powered by a supermassive black hole but instead by shocks, starburst-driven winds or cooling flows.

1.1.2.3 Radio-quiet Quasars

Quasi-stellar objects are very high luminosity AGN so-called because when first observed they resembled faint, star-like points of light. They always show strong optical continuum emission, X-ray continuum emission, and broad and narrow optical emission lines. Quasar host galaxies can be spirals, irregulars, or ellipticals. The majority of quasars (about 90%) are radio-quiet with relatively weaker radio emission than the radio-loud population and lack powerful jets.

1.1.3 Radio-loud AGNs

1.1.3.1 Radio-loud Quasars

Radio-loud quasars make up approximately 5 to 10% of the overall quasar population. These exhibit similar characteristics to their radio-quiet counterparts but with the addition of emission from a jet, and a tendency to have larger host galaxies.

1.1.3.2 Radio Galaxies

Radio galaxies are a class of AGN that are very luminous at radio wavelengths. The host galaxies of radio galaxies are almost always giant ellipticals and often have jets perpendicular to the galactic plane. Based on the appearance of extended radio emission, radio galaxies are subdivided using the Fanaroff-Riley classification scheme. Low Luminosity Class I (abbreviated FR-I) sources are comparatively compact with jets whose luminosity decreases with increasing distance from its host galaxy. High Luminosity Class II (FR-II) sources exhibit increasing luminosity in the lobes, their jets terminating in hotspots. This distinction between classes indicates a difference in energy transfer from core to jets with FR-IIs being the more efficient. In addition, radio galaxies with similar spectra to Seyfert 2 AGNs are referred to as narrow-line radio galaxies (NLRG), while those with broad optical-UV lines similar to Seyfert 1 AGNs are called broad-line radio galaxies (BLRG).

1.1.3.3 Blazars

Blazars comprise two separate AGN classes: optically violent variables (OVVs) and BL Lac objects. Optically violent variables exhibit a high degree of polarisation (up to a few per cent) and are observed to vary greatly (e.g. $\Delta m \approx 0.1$ mag) on time scales of less than a day. The focus of this thesis will be a class of AGN called BL Lac objects. The name BL Lac is derived from BL Lacertae, the prototype of the class. This class is noteworthy for high brightness variability and weakness (or total absence) of spectral lines. Instead, the spectrum of BL Lac objects is dominated by a relatively featureless non-thermal emission continuum covering the entire electromagnetic range.

It is thought that blazars are AGNs with a strong relativistically beamed component orientated close to the line of sight. The observed one-sided core-jet structure found in nearly all blazars on parsec scales is understood to result from relativistic Doppler boosting of emission from a jet of plasma ejected from the vicinity of a supermassive black hole. The outflow in the approaching jet is beamed towards us, while the receding jet becomes too faint to be detected.

1.1.4 AGN Unification

All of the AGN classes are thought to originate from the same type of physical object but viewed under different conditions. A depiction of this basic unification scheme

is shown in Figure 1.2. The upper half of this diagram illustrates how inclination angle and total radio power affect radio-loud AGNs with strong jets. At a viewing angle of close to 0° an observer is almost looking down the barrel of an AGN, giving a blazar that is dominated by relativistic beaming. When the AGN inclination angle is increased an observer sees a quasar/QSO jet. The lower half of Figure 1.2 shows radio-quiet AGNs which lack powerful jets. For Seyfert 1 AGNs, the observer has an almost direct view of the active nucleus explaining while in the case of Seyfert 2 AGNs, the broad line emitting regions are blocked by the dusty torus. This scheme also suggests the primary difference between Seyferts and quasars is the luminosity of the central source. There are issues with this unification scheme, however, especially the relationship between radio-loud and radio-quiet. It has been suggested that radio loudness is a fundamental feature related to the central black hole engine. Blandford (1990) has attempted to qualitatively classify AGNs based on a) mass, b) accretion rate, and c) angular momentum of the central source plus the inclination. Wilson & Colbert (1995) suggest the difference is caused by black hole spin rate with high energies, and high spin rates being associated with larger black holes that have undergone mergers.

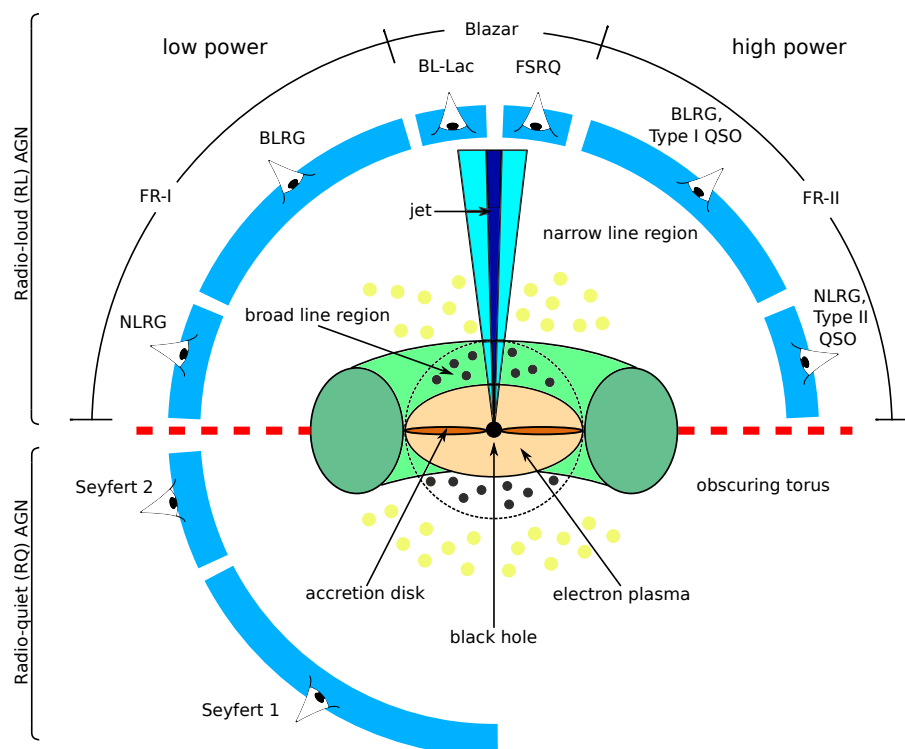


Figure 1.2: Schematic explaining unified model for AGNs. The top half of the diagram shows a radio-loud AGN and the lower half shows a radio-quiet AGN. The AGN features are labeled with arrows. Adapted from Figure 4.16 of Beckmann & Shrader (2012)

1.2 The MOJAVE Program

The MOJAVE (Monitoring Of Jets in Active galactic nuclei with VLBA Experiments) program of Purdue University is a long-term program to monitor radio brightness and polarisation variations in jets associated with active galaxies visible in the northern sky.

The program originally developed out of the 1994–2002 2 cm VLBA survey, which only considered intensity. The MOJAVE-I observations (2002–2006), obtained at 15.3 GHz included full polarisation images for a sample of 135 sources at reasonable intervals for measuring superluminal motion. The MOJAVE-II observations (2006) extended the sample to 192 sources and included polarimetric observations at 8.1, 8.4, 12.1, and 15.3 GHz. The MOJAVE-III (Fermi-era) observations (2007–2013) were carried out at 15.3 GHz only, with 30 AGNs being observed in each 24 hour session.

The new results presented in this thesis will have come from an analysis of VLBI polarisation data for a selection of the AGNs in the MOJAVE-II and MOJAVE-III samples at 5.0, 2.2, 1.8, and 1.45 GHz (6, 13, 17, 21 cm) obtained in 2017 and 2019. Also, a comparison will be made between these 6–21 cm observations and older VLBA observations at four wavelengths between 18 and 22 cm made in 2004 and 2010. These observations were made with the Very Long Baseline Array (VLBA), which consists of 10 radio telescopes spread across the United States from the Virgin Islands to Hawaii. The data enables us to make full polarisation images with an angular resolution of less than 1 milliarcsecond (the apparent separation of a car's headlights, as seen by an astronaut on the Moon).

1.3 Synchrotron Radiation

The following section is based on Chapter 6 of Rybicki & Lightman (1986). The radio emission observed from AGNs consists of synchrotron radiation. Any accelerated charged particle emits electromagnetic radiation. Mildly relativistic electrons whose kinetic energies are comparable with their rest mass $m_e c^2$ emit cyclotron radiation. In the case of ultrarelativistic electrons (kinetic energies $\gg m_e c^2$) synchrotron radiation is produced. Consider the equations of motion for such a relativistic

particle

$$\frac{d}{dt}(\gamma m \vec{v}) = q \vec{v} \times \vec{B} \quad (1.1a)$$

$$\frac{d}{dt}(\gamma m c^2) = q \vec{v} \cdot \vec{E} = 0. \quad (1.1b)$$

Equation 1.1 implies that $\gamma = \text{constant}$ or that $|\vec{v}| = \text{constant}$. From this, it follows that

$$m\gamma \frac{d\vec{v}}{dt} = q \vec{v} \times \vec{B}. \quad (1.2)$$

Separating the velocity into components along the field $\vec{v}_{\parallel}$ and perpendicular $\vec{v}_{\perp}$ we have

$$\frac{d\vec{v}_{\parallel}}{dt} = 0, \quad \frac{d\vec{v}_{\perp}}{dt} = \frac{q}{m\gamma} \vec{v}_{\perp} \times \vec{B}, \quad (1.3)$$

the solution to Equation 1.3 being uniform circular motion. The combination of this uniform circular motion and velocity along the field is a helical motion. The frequency of the rotation is

$$\omega_B = \frac{qB}{\gamma m}. \quad (1.4)$$

Defining the acceleration in the observers frame as $\vec{a} = \frac{d\vec{v}}{dt}$, rearranging Equation 1.2, and expressing in scalar terms we get

$$a = \frac{q v B \sin \beta}{\gamma m}, \quad (1.5)$$

where β , the pitch angle, is the angle between $\vec{v}$ and $\vec{B}$. The power emitted by an accelerated charge in its own rest frame is given by the Larmor formula

$$P' = \frac{q^2 a'^2}{6\pi\epsilon_0 c^3}, \quad (1.6)$$

however, we need to express this relation in the observer's frame. If energy dE' is emitted in time dt' in the rest frame of the particle then in the observer's frame

$$dE = \gamma dE' \quad (1.7a)$$

$$dt = \gamma dt' \quad (1.7b)$$

$$\frac{dE}{dt} = \frac{dE'}{dt'} \quad (1.7c)$$

$$P = P'. \quad (1.7d)$$

Now we use the relationship between acceleration a and a'

$$a'_{\parallel} = \gamma^3 a_{\parallel} \quad \text{parallel to direction of motion} \quad (1.8a)$$

$$a'_{\perp} = \gamma^2 a_{\perp} \quad \text{perpendicular to direction of motion.} \quad (1.8b)$$

In our case $a'_{\parallel} = 0$ and $a'_{\perp} = \gamma^2 a$. Hence, we can express the power emitted in the observer's frame as

$$P = \frac{q^2 \gamma^4 a^2}{6\pi\epsilon_0 c^3}. \quad (1.9)$$

Now subbing in the acceleration from Equation 1.5 we get

$$P = \frac{q^4 \gamma^2 v^2 B^2 \sin^2 \beta}{6\pi\epsilon_0 m^2 c^3}. \quad (1.10)$$

This is the power emitted by a single charge with a pitch angle β . For many such particles, we must average over all angles of β

$$\langle \beta \rangle = \int \frac{\sin^2 \beta d\Omega}{4\pi} \quad (1.11a)$$

$$= \frac{\int_0^{\pi} \int_0^{2\pi} \sin^3 \theta d\theta d\phi}{4\pi} \quad (1.11b)$$

$$= \frac{2\pi}{4\pi} \int_0^{\pi} \sin^3 \theta d\theta \quad (1.11c)$$

$$= \frac{1}{2} \int_0^{\pi} \sin^3 \theta d\theta \quad (1.11d)$$

$$= \frac{2}{3}. \quad (1.11e)$$

Therefore we can say the average power emitted is

$$\langle P \rangle = \frac{q^4 \gamma^2 v^2 B^2}{9\pi\epsilon_0 m^2 c^3}. \quad (1.12)$$

As this is $\propto \frac{1}{m^2}$ we expect the largest contribution to be made by electrons which are 10^3 times less massive than protons. Now we need to discuss the spectrum of synchrotron radiation. We expect the emission to be highly beamed forward in a cone of angular width $\approx \frac{1}{\gamma}$. Radiation from a single electron would appear as a pulse of duration Δt . From the Fourier transform relation we expect a narrow Δt results in a broad Δf . Firstly, we need to roughly estimate Δt . Shown schematically in Figure 1.3 is an observer's view of a pulse.

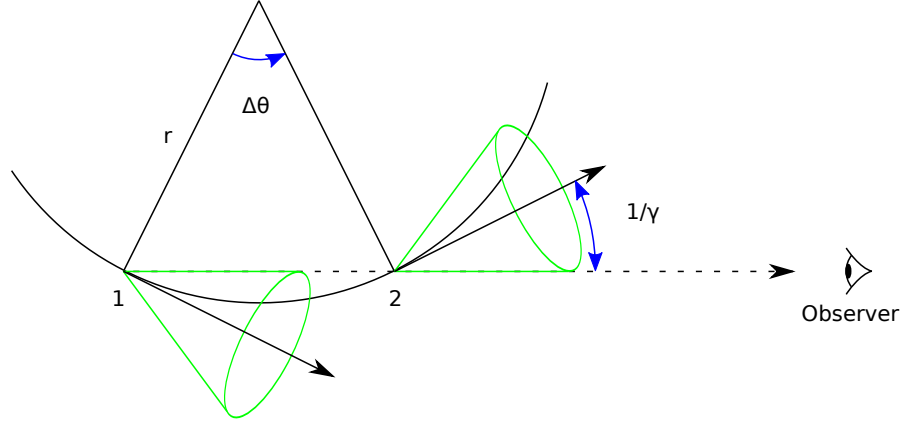


Figure 1.3: Emission cones at various points of an accelerated particle's trajectory. Adapted from Figure 6.2 of Rybicki & Lightman (1986)

From Equation 1.3, the equation of motion of an electron gyrating with radius of rotation r is

$$m \frac{d\vec{v}}{dt} = \frac{qvB \sin \beta}{\gamma} = \frac{mv^2}{r}, \quad (1.13)$$

which can be rearranged using $\omega_B = \frac{qB}{\gamma m}$ to give

$$r = \frac{v}{\omega_B \sin \beta}. \quad (1.14)$$

As the particle is ultrarelativistic we expect Doppler boosting towards the observer to make the pulse duration much shorter than the period of gyration ω_B . This means that the spectrum will be broader than that of the gyration period. Using Equation 1.14 we can say the distance between points 1 and 2 is

$$\Delta s = r \Delta \theta \quad (1.15a)$$

$$= \frac{v}{\omega_B \sin \beta} \cdot \frac{2}{\gamma}, \quad (1.15b)$$

and expressing the distance to pass from point 1 to 2 as $\Delta s = v(t_2 - t_1)$ we can say find the travel time

$$\Delta s = v(t_2 - t_1) \approx \frac{2v}{\gamma \omega_B \sin \beta} \quad (1.16a)$$

$$t_2 - t_1 \approx \frac{2}{\gamma \omega_B \sin \beta}. \quad (1.16b)$$

Let t_1^A and t_2^A be the arrival time of radiation to an observer from points 1 and 2. The difference between times t_1 and t_2 is shorter than the difference between t_1^A and t_2^A

by the amount $\frac{\Delta s}{c}$ which is the time taken to move Δs

$$\Delta t^A = t_2^A - t_1^A = (t_2 - t_1) - \frac{\Delta s}{c} \quad (1.17a)$$

$$= \frac{2}{\gamma \omega_B \sin \beta} \left(1 - \frac{v}{c}\right). \quad (1.17b)$$

At ultrarelativistic speeds, $\gamma \gg 1$, and so $\left(1 - \frac{v}{c}\right) \approx \frac{1}{2\gamma^2}$. With this, Equation 1.17b can be expressed as

$$\Delta t^A \approx \frac{1}{\gamma^3 \omega_B \sin \beta}, \quad (1.18)$$

which indicates the width of the observed pulses is smaller than the gyration period by a factor of $\frac{1}{\gamma^3}$. Further analysis shows that most radiation is emitted at the critical frequency

$$\omega_C = \frac{3}{2} \gamma^3 \omega_B \sin \beta. \quad (1.19)$$

Next, we need to discuss the behaviour of the spectrum. It can be shown that

$$P = \int_0^\infty P(\omega) d\omega = C_1 \int_0^\infty F\left(\frac{\omega}{\omega_C}\right) d\omega, \quad (1.20)$$

where F is a dimensionless function and C_1 is a constant of proportionality. Setting $x = \frac{\omega}{\omega_C}$ the integral can be expressed as

$$P = \omega_C C_1 \int_0^\infty F(x) dx. \quad (1.21)$$

The value of ω_C is known from Equation 1.19 and the constant C_1 is taken to be Equation 1.10. Hence, the power as a function of frequency in a highly relativistic case can now be written as

$$P(\omega) = C_n \frac{q^3 B \sin \beta}{9\pi \epsilon_0 m c} F\left(\frac{\omega}{\omega_C}\right), \quad (1.22)$$

where C_n is the normalisation factor for F . Note that all the factors of γ cancel out except for those contained within ω_C . This allows us to approximate the spectrum with a power law over a short range of frequencies. For this case, we define a spectral index α as

$$P(\omega) \propto \omega^\alpha, \quad (1.23)$$

with α being the positive slope on a $P(\omega)$ versus $\log(\omega)$ plot. This will arise if the distribution of particle energies (Lorentz factors) is a power law

$$N(E) dE = C E^{-p} dE, \quad E_1 < E < E_2, \quad (1.24)$$

or

$$N(\gamma) d\gamma = C\gamma^{-p} d\gamma, \quad \gamma_1 < \gamma < \gamma_2, \quad (1.25)$$

where N is the particle density. C is not necessarily a constant and may vary with pitch angle. The total power generated per unit volume and frequency can be written as an integral of $N(\gamma) d\gamma$ multiplied by the power of a single particle using Equation 1.22 and considering only the proportionalities

$$P_{tot}(\omega) = \int_{\gamma_1}^{\gamma_2} P(\omega) \gamma^{-p} d\gamma \propto \int_{\gamma_1}^{\gamma_2} F\left(\frac{\omega}{\omega_c}\right) \gamma^{-p} d\gamma. \quad (1.26)$$

Let us change the variables of integration to $x \equiv \frac{\omega}{\omega_c}$ and noting that $\omega_c \propto \gamma^2$, we can say

$$P_{tot}(\omega) \propto \omega^{-(p-1)/2} \int_{x_1}^{x_2} F(x) x^{(p-3)/2} dx. \quad (1.27)$$

The limits x_1 and x_2 correspond to γ_1 and γ_2 and are dependent on ω . For sufficiently wide energy limits $x_1 \approx 0$ and $x_2 \approx \infty$, so that the integral in Equation 1.27 is roughly constant. In this case we have

$$P_{tot}(\omega) \propto \omega^{-(p-1)/2}, \quad (1.28)$$

so that the spectral index is related to the particle distribution index p by

$$\alpha = -\frac{p-1}{2}. \quad (1.29)$$

The lifetime of a synchrotron particle can be calculated by dividing the energy of the particle by the power (energy per unit second)

$$\tau_{synch} \approx \frac{E}{P} \quad (1.30a)$$

$$\tau_{synch} \approx \gamma mc^2 \left(\frac{c^4 \gamma^2 v^2 B^2}{9\pi\epsilon_0 m^2 c^3} \right)^{-1} \quad (1.30b)$$

$$\tau_{synch} \approx \frac{9\pi\epsilon_0 m^3 c^5}{e^4 \gamma v^2 B^2}. \quad (1.30c)$$

This indicates that high energy (high γ) electrons radiate more powerfully and have shorter lifetimes. In addition as electrons at high frequencies have shorter lifetimes the spectrum of synchrotron radiation steepens over time.

1.4 Optical Depth

Optical depth describes how much absorption occurs when light travels through an absorbing medium. If the mean free path of a synchrotron photon is greater than the size of a region, then it will pass through this region without being absorbed. This is defined as an *optically thin* region. In contrast, if the mean free path is much smaller than the size of a region, this is defined as an *optically thick* region, and the average photon cannot pass through the region without experiencing re-absorption. Adding together the contributions of an ensemble of electrons at high frequencies we find that synchrotron emission has a characteristic spectrum

$$S_\nu \propto \nu^\alpha, \quad (1.31)$$

where S_ν is the flux density at a frequency ν and α is the spectral index defined earlier in Equation 1.29. At frequencies higher than the turnover frequency (optically thin), flux steadily declines with frequency with $\alpha = -(p-1)/2$. At frequencies below the turnover frequency, there is a significant amount of synchrotron self-absorption where the synchrotron photons are absorbed by the emitting electrons. At these frequencies, the region is optically thick. Theoretical calculations show that in this regime $\alpha = 5/2$. On a logarithmic scale graph, this would correspond to a positive slope of $+5/2$. This is illustrated in Figure 1.4. Astrophysical sources are inhomogeneous, so their actual low-frequency spectral slopes are smaller than $5/2$.

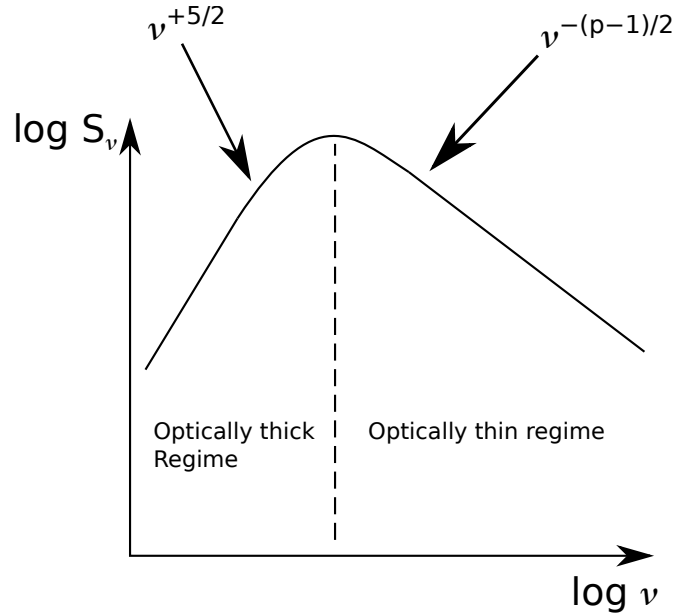


Figure 1.4: Illustration of the spectrum of synchrotron radiation. Figure based on Gabuzda (2008)

Using observations of flux density at different frequencies we can calculate the spectral index of a region. Rearranging Equation 1.31 we can say

$$\alpha(\nu) = \frac{\partial \log S_\nu(\nu)}{\partial \log \nu}. \quad (1.32)$$

The calculated spectral index of a source can hint at its properties. Generally, the core of an AGN is partially optically thick, with a nearly flat or inverted spectrum. The jet emission tends to be optically thin ($\alpha \leq -0.5$), with some flat spectrum regions possibly associated with particle re-acceleration or interaction with the surrounding medium. This manifests in a comparatively high spectral index in the core which decreases with distance out.

When dealing with multifrequency images, the standard theory of extragalactic radio sources predicts a frequency-dependent shift in the location of the VLBI core due to opacity effects in the core region (Blandford & Königl 1979). Reabsorption of synchrotron radiation takes place in the dense region near the central engine of an AGN, which is more efficient at low frequencies. As a result, the peak brightness appears further along the jet axis in lower frequency observations

$$r_c \propto \nu^{-1}, \quad (1.33)$$

where r_c is the core position. To successfully carry out multifrequency analysis and avoid misalignment, images need to be fixed by "core-shifting". Throughout this thesis, each map was corrected for the frequency dependence of the optically thick core position using a cross-correlation technique for aligning the optically thin emission from the jet (Croke & Gabuzda 2008). This method is suitable for use with smooth or weak jets that do not have distinct components at each frequency with which to align the image.

1.5 Faraday Rotation

The following section is based on Chapter 8 of Rybicki & Lightman (1986). A linearly polarised wave can be expressed as a linear superposition of a left and right-hand circularly polarised wave. Together these two waves define the electric vector position angle (EVPA), or polarisation angle χ . For a wave propagating in a vacuum, the RCP and LCP components rotate at the same speed. However, when the wave propagates through a magnetized plasma, a difference in refractive index between

the RCP and LCP component occurs (birefringence) which causes them to propagate at different speeds. This causes the EVPA to change. This phenomenon is called Faraday Rotation. If the fixed magnetic field B_0 is stronger than the field strengths of the propagating wave, then the equation of motion for a local electron is approximately

$$m \frac{d\vec{v}}{dt} = -e\vec{E} - e\vec{v} \times \vec{B}_0, \quad (1.34)$$

where the electron charge $q = -e$. The quantity $\vec{E}$ is the electric field strength of the incident wave. Assuming that the wave is circularly polarised and sinusoidal we have

$$\vec{E}(t) = E_0 e^{-i\omega t} (\vec{e}_1 \mp \vec{e}_2). \quad (1.35)$$

The vectors $\vec{e}_1$ and $\vec{e}_2$ describe dielectric constants along orthogonal axes while the + and – signs refer to right and left hand polarisation respectively. Let us further assume that the wave propagates along the direction of the fixed field $\vec{B}_0$

$$\vec{B} = B_0 \vec{e}_3. \quad (1.36)$$

Inserting Equations 1.35 and 1.36 into Equation 1.34 it can be shown that for a steady state solution $\vec{v}(t)$ has the form

$$\vec{v}(t) = \frac{-ie}{m(\omega \pm \omega_B)} \vec{E}(t), \quad (1.37)$$

where the cyclotron frequency is defined as $\omega_B = \frac{eB_0}{m}$. From this, it is apparent that the right and left circularly polarised waves will propagate through the plasma at different velocities. We can use Equation 1.37 to find the conductivity σ for each component

$$\vec{j} = \sigma \vec{E}(t) = ne\vec{v}(t), \quad (1.38)$$

where $\vec{j}$ is the electron current density and n is the electron number density. Inserting Equation 1.37, the $\vec{E}(t)$ factors cancel and we get

$$\sigma = \frac{ine^2}{m(\omega \pm \omega_B)}. \quad (1.39)$$

We can connect this to the dielectric constant ϵ

$$\epsilon_{R,L} = 1 - \frac{\sigma}{i\epsilon_0\omega} = 1 - \frac{\omega_p^2}{\omega(\omega \pm \omega_B)}, \quad (1.40)$$

where we define the plasma frequency $\omega_p = \sqrt{\frac{ne^2}{m\epsilon_0}}$. The right and left circularly polarised waves travel at differing velocities and so the plane of polarisation of the linearly polarised wave will rotate as it propagates. This effect is Faraday Rotation. After travelling a distance d the vector $\vec{E}$ for a circularly polarised wave undergoes a phase change $\phi = \vec{k} \cdot \vec{d}$, where $\vec{k}$ is the wavenumber. In general if $\vec{k}$ is not constant along the path we have

$$\phi_{R,L} = \int_0^d k_{R,L} ds, \quad (1.41)$$

where

$$k_{R,L} = \frac{\omega}{c} \sqrt{\epsilon_{R,L}}. \quad (1.42)$$

The phase difference introduced between the RCP and LCP is

$$\Delta\theta = \int_0^d (k_R - k_L) ds. \quad (1.43)$$

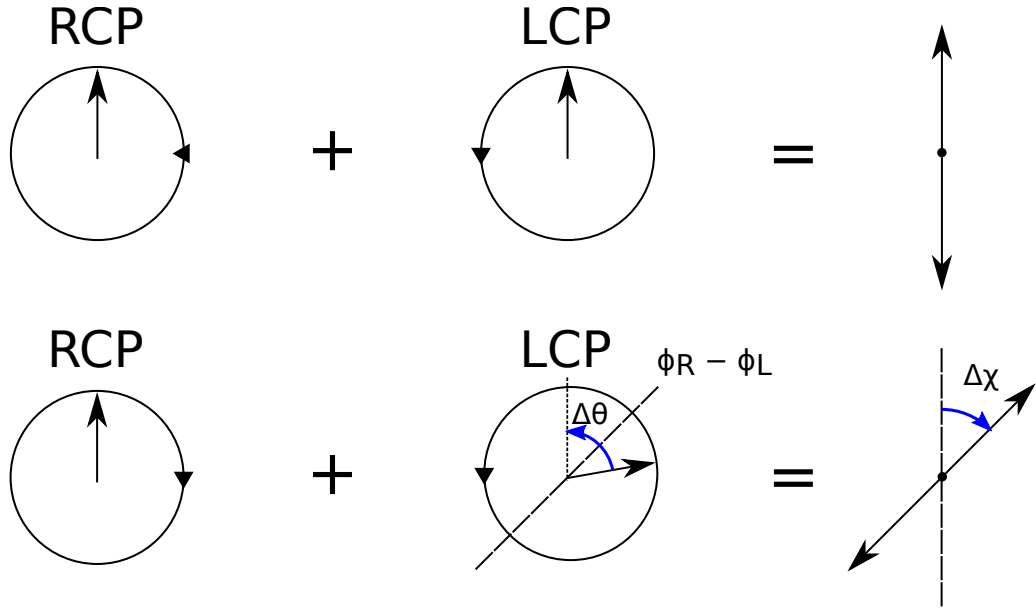


Figure 1.5: Figure showing how LCP and RCP combine to give a particular linear polarisation angle. The top figure shows linear polarisation with no Faraday rotation. The bottom figure has a delay in the LCP. The result of this is a change $\Delta\chi$ in the linear polarisation angle. Diagram adapted from Figure 8.1 of Rybicki & Lightman (1986).

Substituting in Equation 1.40 into Equation 1.42

$$k_{R,L} = \frac{\omega}{c} \left[1 - \frac{\omega_p^2}{\omega(\omega \pm \omega_B)} \right]^{\frac{1}{2}}. \quad (1.44)$$

We can simplify this by approximating $\omega \gg \omega_p$ and $\omega \gg \omega_B$

$$k_{R,L} \approx \frac{\omega}{c} \left[1 - \frac{1}{2} \frac{\omega_p^2}{\omega(\omega \pm \omega_B)} \right] \quad (1.45a)$$

$$\approx \frac{\omega}{c} \left[1 - \frac{1}{2} \frac{\omega_p^2}{\omega^2} \left(1 \pm \frac{\omega_B}{\omega} \right)^{-1} \right] \quad (1.45b)$$

$$\approx \frac{\omega}{c} \left[1 - \frac{1}{2} \frac{\omega_p^2}{\omega^2} \left(1 \mp \frac{\omega_B}{\omega} \right) \right]. \quad (1.45c)$$

We then use this approximation to simplify the term $k_R - k_L$

$$k_R - k_L = \frac{\omega}{c} \left[-\frac{1}{2} \frac{\omega_p^2}{\omega^2} \left(-\frac{\omega_B}{\omega} - \frac{\omega_B}{\omega} \right) \right] \quad (1.46a)$$

$$= \frac{\omega}{c} \frac{\omega_p^2}{\omega^2} \frac{\omega_B}{\omega} \quad (1.46b)$$

$$= \frac{\omega_p^2}{\omega^2} \frac{\omega_B}{c}. \quad (1.46c)$$

Finally, we can express the phase difference $\Delta\theta$ between R and L by subbing this into Equation 1.43

$$\Delta\theta = \frac{e^3}{m^2 \epsilon_0 c \omega^2} \int_0^d nB \cdot ds. \quad (1.47)$$

We need to find the relation between $\Delta\theta$ and the rotation of the linear polarisation angle $\Delta\chi$. By symmetry $\Delta\chi = \frac{1}{2}\Delta\theta$. Conventionally, $\Delta\chi$ is expressed in units of radians and in terms of λ^2 instead of ω^2

$$\Delta\chi = \frac{1}{2} \frac{e^3}{m^2 \epsilon_0 c} \left(\frac{\lambda}{2\pi c} \right)^2 \int_0^d nB \cdot ds \quad (1.48a)$$

$$= \left[\frac{e^3}{8\pi^2 m^2 \epsilon_0 c^3} \int_0^d nB \cdot ds \right] \lambda^2 \quad (1.48b)$$

$$= \text{RM} \cdot \lambda^2, \quad (1.48c)$$

where we have introduced the Faraday rotation measure (RM) which by convention has units of radians per metre squared. The change in the polarisation angle is proportional to the wavelength squared. As per this derivation, this formula only holds if the direction of $\vec{B}$ is always along the line of sight. However it can be shown

that this formula holds in general if we use $B_{\parallel}$, the component of $\vec{B}$ along the line of sight. As in Burn (1966), we can then write the following expression

$$\chi = \chi_0 + \text{RM}\lambda^2, \quad (1.49)$$

where χ is the observed polarisation angle, χ_0 is the original (intrinsic) polarisation angle upon emission and RM is the rotation measure. In general, the rotation measure can be estimated by measuring the linear polarisation angle χ at several wavelengths. From measuring RM, we can infer the value of the integral $\int_0^d nB_{\parallel} \cdot ds$ although it is difficult to disentangle the contribution from electron density n_e and the magnetic field. Despite this, if the sign of the rotation measure changes it is a clear indication of a change in direction of the $\vec{B}$ field. In the case of linear polarisation associated with synchrotron radiation, RM measurements allow us to picture the 3D structure of magnetic fields around astronomical objects.

1.6 Helical Magnetic Fields in AGN Jets

The relativistic jets of AGNs seem to originate in a region close to the central black hole. Suggested processes include extraction of energy from the black hole spin (Blandford & Znajek 1977) or from the magnetized accretion disk (Blandford & Payne 1982).

As mentioned earlier, the exact collimation mechanism of these jets is unknown. One possible explanation for the high collimation is a helical magnetic field structure in the jet. Theoretical studies Nakamura et al. (2001), Lovelace et al. (2002) have predicted the development of such a helical jet, arising from the "winding up" of an initial "seed" field by the rotation of the central accreting objects.

The primary objective of this project was to identify, where possible, evidence that helical fields are present in the jets of the sources that were studied. Although it is not possible to directly measure the strengths of the magnetic fields in AGN jets, their orientation can be inferred from the direction of the observed linear polarisation. The remainder of this chapter will be the discussion of different aspects of jet polarisation and how they lend insight into its magnetic field structure.

1.6.1 Polarisation Structure

As discussed earlier, the synchrotron radiation emitted from AGN jets can be highly linearly polarised. It also has weak intrinsic circular polarisation typically less than 0.1%, which was not examined in this project.

By IAU convention, the electric vector position angle (EVPA), or polarisation angle χ , which indicates the plane of polarisation, is measured starting from North and increasing counter-clockwise, through East.

In an optically thin region, the EVPA of polarised synchrotron emission is perpendicular to the projection of the magnetic field onto the plane of the sky. If a helical magnetic field is present in the jet, the magnetic field lines will be roughly aligned with the jet direction at the edges, and orthogonal to the jet direction in the centre. Given EVPAs perpendicular to the line-of-sight magnetic field, this will give rise to a "spine-sheath" EVPA pattern, shown in Figure 1.6. Hence, sources where such a "spine-sheath" structure is observed, can be considered candidate helical field hosts. Numerous studies have found examples of this spine-sheath structure in AGN jets such as Pushkarev et al. (2005) and Gabuzda et al. (2014).

This is somewhat of a simplification, with this exact structure coming about when the observer is looking at the jet at a very specific viewing angle. In reality, the projection of a helical magnetic field onto the plane of the sky depends on two parameters: viewing angle δ' and the helix pitch angle γ' . The different polarisation structures in the presence of a helical field for varying pitch angles and viewing angles were analysed in detail in Murphy et al. (2013). Depending on these particular parameters, the EVPA structure observed can be perceived to be entirely longitudinal (EVPAs parallel to jet), entirely transverse (EVPAs perpendicular to jet), transverse on the edges of the jet, and longitudinal along the spine (i.e. the spine-sheath structure) or transverse on one side of the jet but longitudinal on the other side. Knowledge of this is essential for interpreting the observed polarisation structure.

1.6.2 Fractional Polarisation

Fractional polarisation $m = \frac{P}{I}$ is the ratio of polarised intensity to total intensity, where $P = \sqrt{Q^2 + U^2 + V^2}$, is the total polarisation intensity expressed in Stokes parameters. For synchrotron radiation at an optically thin frequency, if the ambient magnetic field were completely uniform and all the electrons were circling perpendicular to this field (a pitch angle of 90°) we theoretically would observe 100%

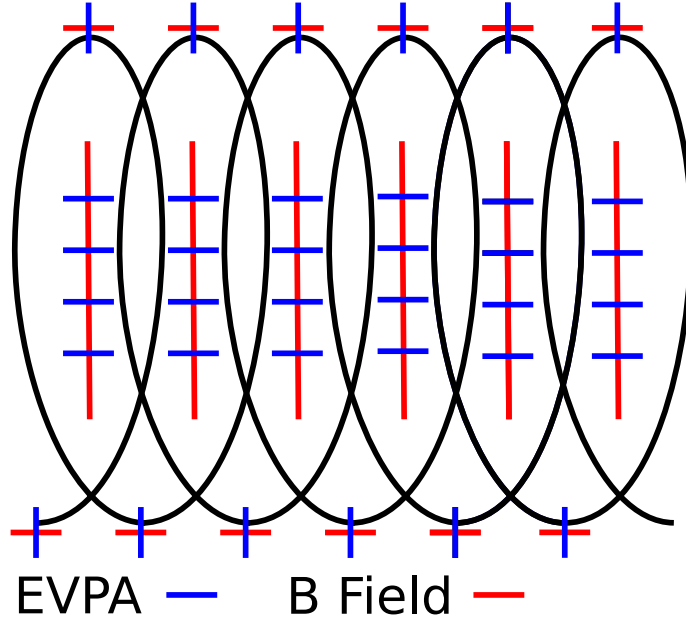


Figure 1.6: Idealized schematic showing how a spine-sheath pattern could be formed.

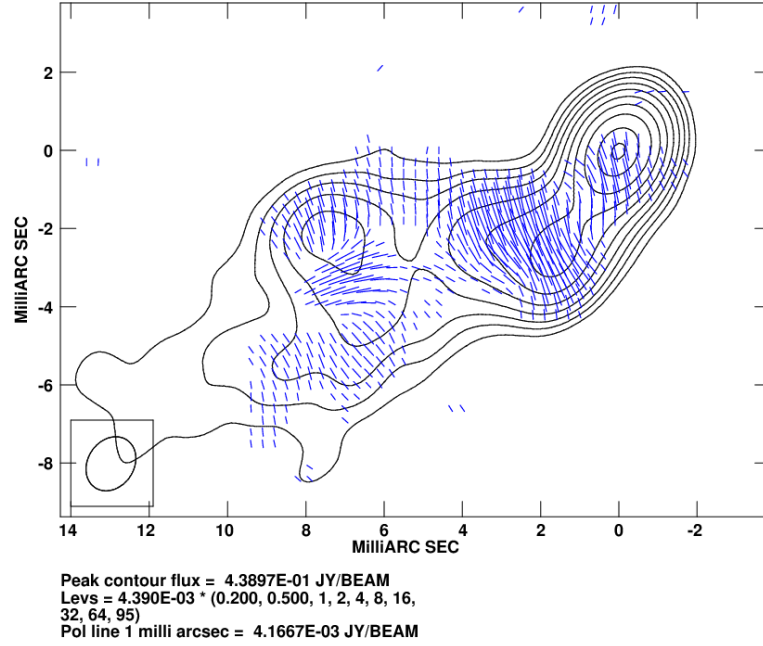


Figure 1.7: Real spine-sheath structure in optically thin jet of Markarian 501 at 8.4 GHz. Figure from Coughlan & Gabuzda (2013).

linear polarisation (Gabuzda 2008). However, in reality, assuming a uniform field, the pitch angles are randomly distributed, fractional polarisation can reach a maximum of 75% in the optically thin regime.

Generally, we can imagine the polarisation E vector of radiation to consist of two components: One perpendicular to the ambient magnetic field (in the plane of polarisation). And the other parallel to the magnetic field. In the optically thin

regime, the perpendicular component dominates, so overall E and the plane of polarisation is perpendicular to the B field. In contrast, in optically thick regions the perpendicular component of the E is more likely to be absorbed and never leave the region than the component parallel to the B field. This means a lower fractional polarisation. In summary:

- Optically thin regime: The observed plane of polarisation is perpendicular to the B field and the degree of linear polarisation can reach $\approx 75\%$
- Optically thick regime: The observed plane of polarisation is parallel to the B field and the degree of linear polarisation no more than about 10–15%

Overall, fractional polarisation is a good indicator of the order of a magnetic field with a regular ordered field producing high fractional polarisation and a tangled or disordered field producing significantly less. In the case of a helical magnetic field, the line-of-sight magnetic field lines will tend to be more ordered at the edges (as they are all pointing in the same direction) and more disordered towards the centre of the jet (as the field lines cross over each other). Hence, if a jet is host to a helical magnetic field, one expects the fractional polarisation to rise at the edges of the jet.

In addition to this, variations in fractional polarisation across the jet can also be attributed to a variety of physical processes inside the jet. A compact feature with higher than usual fractional polarisation and polarisation angles aligned parallel to the jet direction (implying an orthogonal magnetic field) may indicate the presence of a transverse shock in the jet. Cawthorne et al. (2013) have described the EVPA structure and fractional polarisation pattern corresponding to the presence of a conical shock in an AGN jet and found evidence of such a shock in the jet of J1800+7828.

1.6.3 Rotation Measure Maps

It has previously been suggested that a helical field structure would result in a transverse RM gradient across the jet, due to the systematic change in the line-of-sight B field component on which the RM value is dependent (Perley et al. 1984, Blandford 1993). From Equation 1.49 we know that if a source has been observed at multiple wavelengths, the RM at a point in the source can be estimated by plotting χ_{obs} against λ^2 . The slope of this plot will give an estimate of the RM value at that point. Figure 1.8 illustrates such a RM measurement using polarisation observations at four wavelengths: 6, 13, 17, and 21 cm.

Figure 1.9 shows a schematic of a hypothetical helical magnetic field in an AGN jet viewed from the side. At the top of the jet, the magnetic field lines lie in the direction of the line of sight, so that the line-of-sight magnetic field component is at a positive maximum. In this part of the jet, positive RM values are expected. At the bottom, the field lines are counter to the line of sight direction. Thus, a negative value for RM is expected. In the centre, the field lines are perpendicular to the line of sight, so the line-of-sight magnetic field, and therefore the RM, is zero. Hence, if a helical field is present in the jet, the value of RM is expected to change across the jet, transverse to the jet direction. Whether or not the RM values change sign across the jet depends on the angle at which the helical magnetic field is viewed. However, a statistically significant gradient is enough to suggest the possibility of a toroidal or helical magnetic field. Statistically significant transverse RM gradients across the parsec-scale jets have been identified in several AGNs in recent times (Gabuzda et al. 2018).

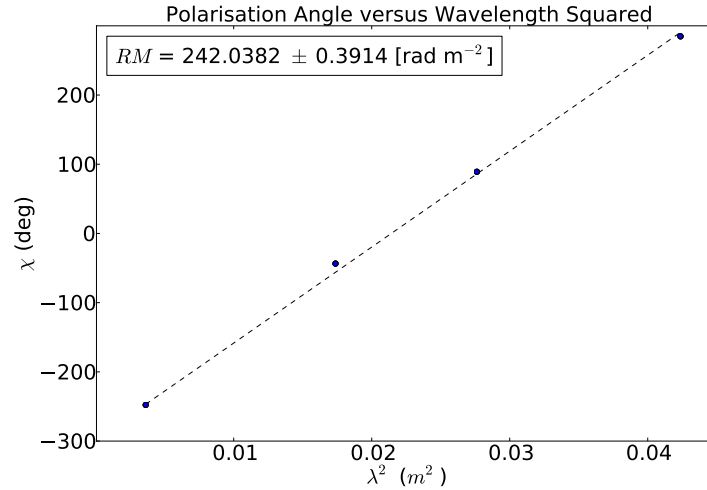


Figure 1.8: Figure showing an example of a χ versus λ^2 fit for a region of the source J0121+1149. The data gives a fitted rotation measure of $RM = 242.038 \text{ rad m}^{-2}$ and an intrinsic polarisation angle of $\chi_0 = -297.064^\circ$.

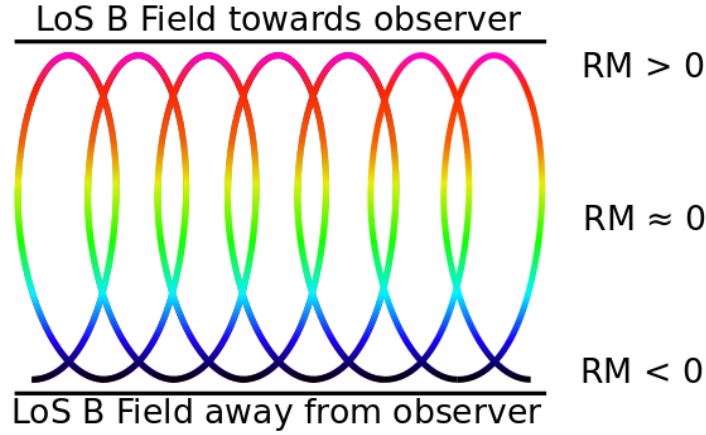


Figure 1.9: Schematic of helical field in jet, showing the gradual change in rotation measure sign from positive to negative expected with this structure.

Studies of particular sources have shown reversals in transverse rotation measure gradients (Mahmud et al. 2013, Gabuzda et al. 2018). This indicates that the orientation of the line-of-sight magnetic field associated with the Faraday rotation changes with either time or distance from the centre of activity.

One possibility suggested in O’Sullivan & Gabuzda (2006) is that a bend in the inner jet changes the observer’s viewing angle and therefore the side of the helical field with dominant polarisation. This produces RMs with different signs in different lengths of the jet. Another possible explanation is that these RM sign reversals correspond to locations where the helical field undergoes a kink or reconnection. If before a change in helicity the line-of-sight B field is pointing towards the observer and after the change, further down the jet it will be pointing away and an opposite RM sign will be observed.

However, the explanation that is most favoured is that the magnetic field of the jet has a "nested helical field" structure, with two regions of helical magnetic field, near the jet axis and further out, with the two regions having oppositely directed azimuthal magnetic fields. A reversal in the direction of the transverse Faraday rotation measure across the jet will be observed if the region dominating the Faraday rotation integral switches from the inner region to the outer region or vice versa.

Chapter 2

Theory of Radio Astronomy

A single radio telescope coherently sums electric fields over an aperture of size D . For this, diffraction theory applies and the angular resolution in radians is

$$\theta_{rad} = \frac{\lambda}{D}. \quad (2.1)$$

This indicates that to improve resolution at a given wavelength, all one must do is increase the size of the dish. However, due to the cost and additional problems caused by gravitational sagging and thermal expansion, the largest contemporary fully steerable dishes such as those at Green Bank and Effelsberg are only 100 m in diameter. For radiation at a wavelength of 21 cm, this results in a poor resolution of about 0.0021 radians or 7.2 arcminutes.

To achieve sub-arcsecond resolution an interferometer is used. The simplest radio interferometer consists of two radio telescopes whose signals are correlated. The line connecting two antennas in an interferometer is called the baseline. The resolution of an interferometer goes roughly as the length of the longest baseline it contains. Thus, an interferometer is comparable in its resolution to a single dish the size of the longest baseline. Very Long Baseline Interferometry (VLBI) utilizes this dependence on baseline length. VLBI arrays, such as the European VLBI Network (EVN) in Europe and the Very Long Baseline Array (VLBA) in the United States host baselines up to thousands of kilometres long, allowing for a very high resolution to be achieved.

2.1 Basics of Radio Interferometry

The following section uses Thompson (1999) and Chapter 3 of Condon & Ransom (2016) as references. The simplest radio interferometer is a pair of radio telescopes whose voltage outputs are correlated (multiplied and averaged in time). A basic 2 element interferometer is shown schematically in Figure 2.1. The simplest case involves an interferometer observing a distant point source. $\hat{s}$ is the unit vector that points from the two antennas to the distant target radio source. $\vec{B}_0$ refers to the baseline vector which points from antenna 1 to antenna 2. Plane waves from this source must travel an extra distance $\vec{B}_0 \cdot \hat{s}$ to reach antenna 1. Hence, the wavefront from the source arrives at antenna 1 a time τ_g after the antenna 2. We call this the geometrical delay and is defined as

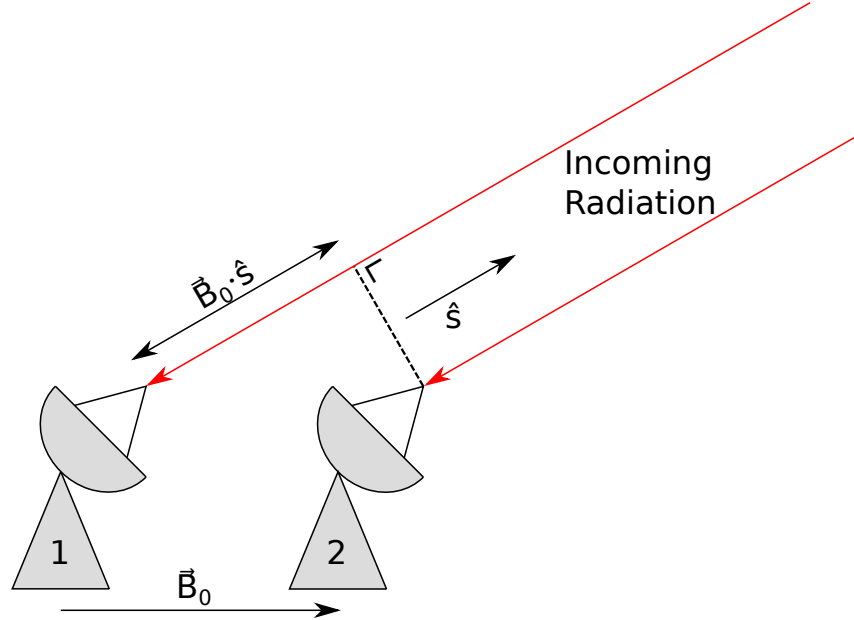


Figure 2.1: Schematic of a two-element interferometer.

$$\tau_g = \frac{\vec{B}_0 \cdot \hat{s}}{c}, \quad (2.2)$$

where c is the speed of light. The (real-valued) output voltages of the antennas in response to the incoming electromagnetic wave are given as follows

$$v_1 = V \cos(\omega t) \quad (2.3a)$$

$$v_2 = V \cos(\omega(t - \tau_g)), \quad (2.3b)$$

where $\omega = 2\pi f$ is the angular frequency. The product of v_1 and v_2 is expressed as

$$v_1 v_2 = V^2 (\cos(\omega t) \cos(\omega(t - \tau_g))) \quad (2.4a)$$

$$= \frac{V^2}{2} (\cos^2(\omega t) \cos(\omega \tau_g) + \cos(\omega t) \sin(\omega t) \sin(\omega \tau_g)), \quad (2.4b)$$

which uses the trigonometric identity $\cos(x - y) = \cos x \cos y + \sin x \sin y$. Averaging over time, the correlator response R_c of the two-element interferometer with a "cosine" correlator is

$$R_c = \langle v_1 v_2 \rangle = \frac{V^2}{2} (\cos(\omega \tau_g) \langle \cos^2(\omega t) \rangle + \sin(\omega \tau_g) \langle \cos(\omega t) \sin(\omega t) \rangle) \quad (2.5a)$$

$$= \frac{V^2}{2} \left(\cos(\omega \tau_g) \times \frac{1}{2} + \sin(\omega \tau_g) \times 0 \right) \quad (2.5b)$$

$$= \frac{V^2}{2} \cos(\omega \tau_g). \quad (2.5c)$$

The voltages V_1 and V_2 are proportional to the electric field produced by the source multiplied by the voltage gains of the two antennas and receivers. Thus the correlator output amplitude $\frac{V^2}{2}$ is proportional to the intensity I of the point source

$$R_c \propto I \cos\left(\frac{2\pi c}{\lambda} \frac{\vec{B}_0 \cdot \hat{s}}{c}\right) \quad (2.6a)$$

$$\propto I \cos(2\pi \vec{B} \cdot \hat{s}), \quad (2.6b)$$

where $\vec{B} = \frac{B_0}{\lambda}$. As with any real valued function, the arbitrary source brightness distribution, can be written as the sum of even (symmetric) and odd (anti-symmetric) parts: $I = I_E + I_O$. However, the even cosine function in R_c is sensitive only to the even part I_E . To detect the odd part I_O we need a "sine" correlator with an odd output, $R_s = \frac{V^2}{2} \sin(\omega \tau_g)$. This can be achieved through use of a second correlator that introduces a $\frac{\pi}{2}$ rad = 90° phase delay into the voltage output of one antenna.

With this in mind, having considered a point source, we can now derive the interferometer response to an extended source, by considering it to be the sum of many point sources. If the original point source we have considered is at the origin, all the other point sources can be described as being separated from it by some vector $\vec{a}$ in the plane of the sky directed to the location of the point source from the "phase centre", corresponding to the direction of $\hat{s}$. The complex correlator response

to any one of these point sources is given by

$$R_c - iR_s \propto I \cos(2\pi \vec{B} \cdot (\vec{a} + \hat{s})) - iI \sin(2\pi \vec{B} \cdot (\vec{a} + \hat{s})). \quad (2.7)$$

The full complex response of the interferometer to the extended source is the integral of the above over $\vec{a}$

$$R_c - iR_s \propto \int_{-\infty}^{+\infty} I(\vec{a}) \cos(2\pi \vec{B} \cdot (\vec{a} + \hat{s})) d\vec{a} - i \int_{-\infty}^{+\infty} I(\vec{a}) \sin(2\pi \vec{B} \cdot (\vec{a} + \hat{s})) d\vec{a} \quad (2.8a)$$

$$\propto \int_{-\infty}^{+\infty} I(\vec{a}) e^{-2\pi i \vec{B} \cdot (\vec{a} + \hat{s})} d\vec{a} \quad (2.8b)$$

$$\propto e^{-2\pi i \vec{B} \cdot \hat{s}} \int_{-\infty}^{+\infty} I(\vec{a}) e^{-2\pi i \vec{B} \cdot \vec{a}} d\vec{a} \quad (2.8c)$$

$$\equiv e^{-2\pi i \vec{B} \cdot \hat{s}} V(\vec{B}), \quad (2.8d)$$

where $V(\vec{B})$ is the complex visibility function. It can be clearly seen that $V(\vec{B})$ forms a Fourier transform pair with $I(\vec{a})$

$$V(\vec{B}) = \int I(\vec{a}) e^{-2\pi i \vec{B} \cdot \vec{a}} d\vec{a} \quad (2.9a)$$

$$I(\vec{a}) = \int V(\vec{B}) e^{2\pi i \vec{B} \cdot \vec{a}} d\vec{B}. \quad (2.9b)$$

As the field of view of the interferometer is very small we can consider that area of the celestial sphere to be a flat surface parallel to the ground where the baseline is located. Hence $\vec{a}$ is perpendicular to $\hat{s}$ and $\vec{B} \cdot \vec{a} \approx \vec{b} \cdot \vec{a}$ where $\vec{b}$ is the baseline projected onto the sky. The vectors $\vec{a}$ and $\vec{b}$ can be decomposed into coordinates in two dimensions. We can choose the coordinates to point North and East. Hence $\vec{a} \rightarrow (x, y)$ and $\vec{b} \rightarrow (u, v)$ where (u, v) are the baseline coordinates on the ground, and (x, y) are the coordinates on the celestial sphere. This system is shown schematically in Figure 2.2. The Fourier transform pair can then be written as

$$V(u, v) = \int I(x, y) e^{-2\pi i(ux+vy)} dx dy \quad (2.10a)$$

$$I(x, y) = \int V(u, v) e^{2\pi i(ux+vy)} du dv. \quad (2.10b)$$

So, in theory, if $\langle v_1 v_2 \rangle$ is known the visibility data $V(u, v)$ can be found, and knowing $V(u, v)$ allows the intensity distribution $I(x, y)$ to be found via Fourier transform. To accurately recreate $I(x, y)$ a large number of antennas covering a large range of (u, v) coordinates is needed.

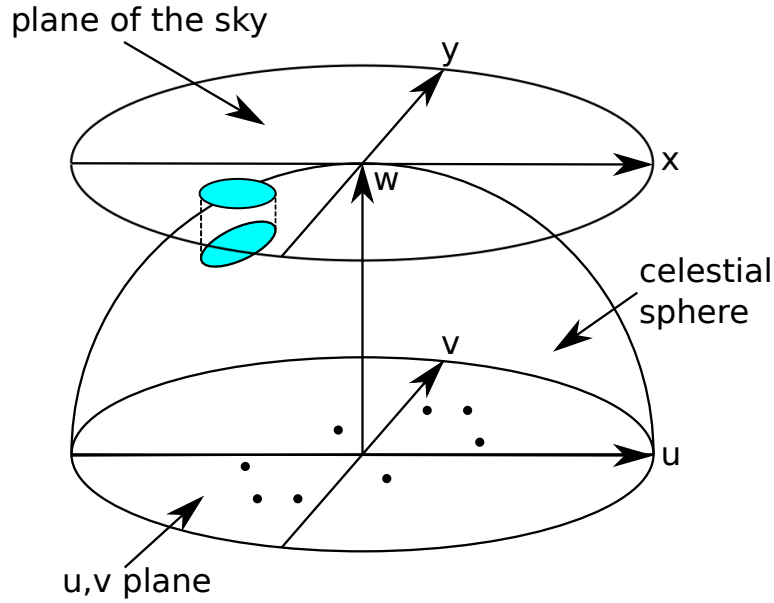


Figure 2.2: Schematic showing the relation between the sky coordinates and those on the ground. The sky dome is approximated as a flat plane. Image credit: Dale E. Gary, NJIT.

2.2 Deconvolution with the CLEAN Algorithm

The following section uses Briggs et al. (1999) and Cornwell & Braun (1989) as references. After calibration, the Equation 2.10b is used to perform an inverse Fourier transform on the visibility data to produce an image. In practice, an array of radio telescopes only takes measurements at certain baselines and this only provides a partial sampling of the visibility function $V(u, v)$. A sampling function $S(u, v) = \sum_k \delta(u - u_k, v - v_k)$ can be defined to equal 1 in the sampled parts of the uv plane and 0 in the unsampled parts. The sampled visibility function $S(u, v) V(u, v)$ is the actual data provided by the array. Hence the result of an observation is a "dirty image"

$$I_D(x, y) = \int S(u, v) V(u, v) e^{2\pi i(ux + vy)} du dv. \quad (2.11)$$

In the image plane, the dirty image (the observed source structure) is the convolution of the true source structure $I(x, y)$ and the Fourier transform of the

sampling function, called the dirty beam $B(x, y)$

$$I_D(x, y) \equiv \mathcal{F}\{S(u, v)\} * \mathcal{F}\{V(u, v)\} \quad (2.12a)$$

$$I_D(x, y) \equiv I(x, y) * B(x, y), \quad (2.12b)$$

where $*$ signifies convolution. The dirty beam is the point spread function of your observation and is entirely dependent on the values of (u, v) at which observations are made. Due to the gaps in the (u, v) coverage, large positive or negative sidelobes may be present in the dirty beam. These are symmetric irregularities away from the beam centre which contaminate the dirty image and obscure fainter structure. We define the dirty beam as

$$B(x, y) = \int S(u, v) e^{2\pi i(ux+vy)} du dv. \quad (2.13)$$

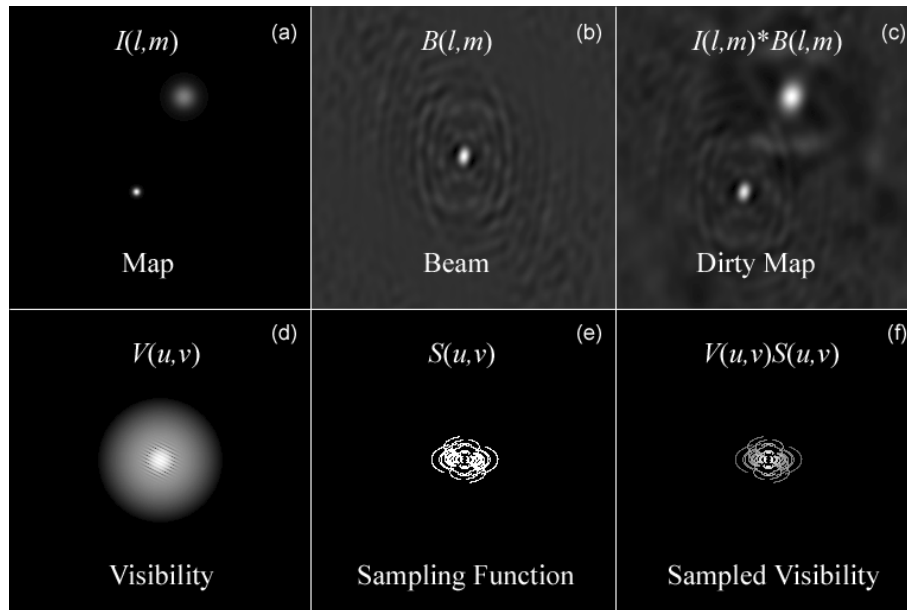


Figure 2.3: Illustration of the relationship between intensity and visibility domains with the top three panels being the intensity and the bottom three being the visibility domain. Note, in this diagram the intensity domain units are referred to as (l, m) and not (x, y) . a) An example (model) sky map. Note that there are no sidelobes. b) is the dirty beam. c) is the dirty map that results from the Fourier transform of the sampled visibilities. This is equivalent to the convolution of the map in (a) with the dirty beam in (b). d) is the complete visibility plane. The Fourier transform of this gives a). e) is the sampling function of the array, whose Fourier transform gives the dirty beam in (b). f) is the product of panels (d) and (e), representing the sampled visibilities. These are the actual measurements from the array. Image credit: Dale E. Gary, NJIT.

To recover the true source structure and improve image quality, it is typically

required to remove the effects of the dirty beam in Equation 2.12b by performing deconvolution on your visibility data. The most basic method of deconvolution is CLEAN algorithm first described in Högbom (1974). The algorithm is most commonly applied in the image plane. This algorithm assumes that the radio sky can be represented by some number of point sources (delta functions). The algorithm effectively reconstructs information in the (u, v) plane. The CLEAN algorithm consists of the following steps.

1. Calculate the discrete Fourier transform of the sampled visibility function data to obtain the dirty map.
2. Find the peak of the dirty map and assume that the emission at this point is real and not the result of any sidelobes.
3. Multiply the dirty beam by some fraction γ (e.g. 0.1) of the dirty map at that point and subtract this from the map with the dirty beam peak at the position of this point. This essentially takes out the contribution of part of the emission at that point from every point in the map, including all its sidelobes. The fraction γ is called the "loop gain" and is chosen such that $0 \leq \gamma \leq 1$.
4. The location and amplitude of the peaks are added as delta functions to a model image (a list of "CLEAN components").
5. Repeat steps 2–4 until the peak that is found is comparable to the noise level (i.e. you've found all the real emission).
6. Convolve the final model image consisting of CLEAN components with an idealized "CLEAN beam"—an elliptical Gaussian fitted to the central lobe of the dirty beam; essentially the dirty beam without its sidelobes. This is called the "CLEAN map".
7. Add the residual dirty map to include any extended structure not modeled well by the CLEAN procedure.

Using this method, removing part of the contribution of the brightest regions (together with their associated sidelobes) gradually reveals regions of weaker emission. If initial amplitude and phase calibration was done correctly then the map should accurately reflect the true source structure.

The CLEAN algorithm also plays a major part in the process of self-calibration (see Section 2.4.3). Self-calibration uses your estimated source structure to better calibrate the antenna-based complex gains (i.e. amplitudes and phases) as a function of time. This is an iterative process. Taking the model of the image made in

step 4 of the CLEAN algorithm the phases are corrected over a short time interval (compared to the coherence time) to match the model. This makes some improvement to the signal-to-noise ratio and allows for a deeper CLEAN and results in a better model. The phases may be corrected multiple times before the amplitudes can also be corrected. Subsequent amplitude corrections are carried out on shorter and shorter time scales.

2.3 Polarisation in Interferometry

The following section is based on Chapter 2 of Rybicki & Lightman (1986) as well as the paper Conway & Kronberg (1969). A monochromatic plane electromagnetic wave can be described as follows

$$\vec{E} = \hat{a}_1 E_0 e^{i(\vec{k} \cdot \vec{r} - \omega t)} \quad (2.14a)$$

$$\vec{B} = \hat{a}_2 B_0 e^{i(\vec{k} \cdot \vec{r} - \omega t)}, \quad (2.14b)$$

where $\hat{a}_1$ and $\hat{a}_2$ are perpendicular unit vectors, E_0 and B_0 are complex constants and $\hat{a}_1 \times \hat{a}_2 = \vec{k}$ where $\vec{k}$ is the direction of propagation. Such waves are linearly polarised.

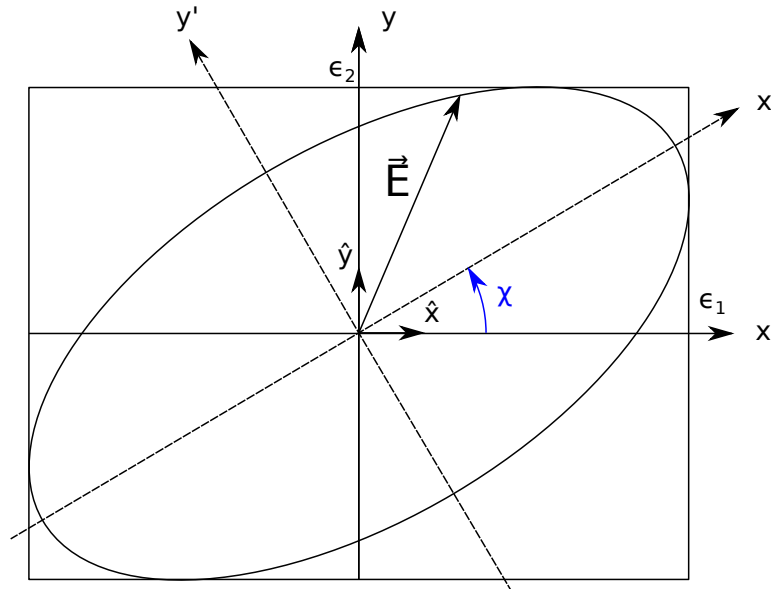


Figure 2.4: Rotation of x and y electric field components by angle χ to coincide with principal axes of polarisation ellipse. Based on Figure 2.4 of Rybicki & Lightman (1986).

Let us examine the electric vector at an arbitrary point ($r = 0$). The magnetic vector simply remains perpendicular with the same amplitude. The electric vector is the real part of

$$\vec{E} = (\hat{x}E_1 + \hat{y}E_2) e^{-i\omega t} = \vec{E}_0 e^{-i\omega t}. \quad (2.15)$$

The complex amplitudes E_1 and E_2 can be expressed as

$$E_1 = \mathcal{E}_1 e^{i\phi_1}, \quad E_2 = \mathcal{E}_2 e^{i\phi_2}. \quad (2.16)$$

The physical (real) components of the electric field along the $\hat{x}$ and $\hat{y}$ directions can be written as

$$E_x = \mathcal{E}_1 \cos(\omega t - \phi_1), \quad E_y = \mathcal{E}_2 \cos(\omega t - \phi_2). \quad (2.17)$$

Each component oscillates with different amplitudes and phases. These equations describe the tip traced out by $\vec{E}$ on the (x, y) plane. In general, $\vec{E}$ traces out an ellipse defined with respect to its principal axes x' and y' . The general equation of an ellipse with respect to its own principal axes is

$$\frac{E_x'^2}{a^2} + \frac{E_y'^2}{b^2} = 1. \quad (2.18)$$

We can set

$$\frac{E_x'^2}{a^2} = \cos^2(\omega t) \implies E_x' = \pm a \cos(\omega t) \quad (2.19a)$$

$$\frac{E_y'^2}{b^2} = \sin^2(\omega t) \implies E_y' = \pm b \sin(\omega t). \quad (2.19b)$$

Now we parameterise a and b in terms of an amplitude $\mathcal{E}_0$ and a phase β such that $-\frac{\pi}{2} \leq \beta \leq \frac{\pi}{2}$

$$a = \mathcal{E}_0 \cos(\beta) \quad (2.20a)$$

$$b = \mathcal{E}_0 \sin(\beta). \quad (2.20b)$$

This then gives

$$E_x' = \mathcal{E}_0 \cos(\beta) \cos(\omega t) \quad (2.21a)$$

$$E_y' = -\mathcal{E}_0 \sin(\beta) \sin(\omega t). \quad (2.21b)$$

With the above parameterisation the ellipse rotates clockwise for $0 \leq \beta \leq \frac{\pi}{2}$ and counter clockwise for $-\frac{\pi}{2} \leq \beta \leq 0$ as viewed by an observer towards whom the wave is propagating. These scenarios are right and left handed elliptical polarisation. In the

case where $\beta = \pm \frac{\pi}{4}$ the ellipse is a circle and this is designated "circular polarisation". Consider now the case where this ellipse traced out by $\vec{E}$ is tilted by an angle χ to the x and y axes

$$E_x = E'_x \cos(\chi) - E'_y \sin(\chi) \quad (2.22a)$$

$$E_y = E'_x \sin(\chi) + E'_y \cos(\chi). \quad (2.22b)$$

This is equivalent to applying a rotation matrix to E' from Equation 2.21. This gives

$$E_x = \mathcal{E}_0 (\cos(\beta) \cos(\chi) \cos(\omega t) + \sin(\beta) \sin(\chi) \sin(\omega t)) \quad (2.23a)$$

$$E_y = \mathcal{E}_0 (\cos(\beta) \sin(\chi) \cos(\omega t) - \sin(\beta) \cos(\chi) \sin(\omega t)), \quad (2.23b)$$

which is equivalent to Equation 2.17 if we take

$$\mathcal{E}_1 \cos(\phi_1) = \mathcal{E}_0 \cos(\beta) \cos(\chi) \quad (2.24a)$$

$$\mathcal{E}_1 \sin(\phi_1) = \mathcal{E}_0 \sin(\beta) \sin(\chi) \quad (2.24b)$$

$$\mathcal{E}_2 \cos(\phi_2) = \mathcal{E}_0 \cos(\beta) \sin(\chi) \quad (2.24c)$$

$$\mathcal{E}_2 \sin(\phi_2) = -\mathcal{E}_0 \sin(\beta) \cos(\chi). \quad (2.24d)$$

Hence, if we are given $\mathcal{E}_1$, ϕ_1 , $\mathcal{E}_2$, and ϕ_2 we can solve for the polarisation parameters $\mathcal{E}_0$, β , and χ . This can be done conveniently using the Stokes parameters

$$I = \mathcal{E}_1^2 + \mathcal{E}_2^2 = \mathcal{E}_0^2 \quad (2.25a)$$

$$Q = \mathcal{E}_1^2 - \mathcal{E}_2^2 = \mathcal{E}_0^2 \cos(2\beta) \cos(2\chi) \quad (2.25b)$$

$$U = 2\mathcal{E}_1\mathcal{E}_2 \cos(\phi_1 - \phi_2) = \mathcal{E}_0^2 \cos(2\beta) \sin(2\chi) \quad (2.25c)$$

$$V = 2\mathcal{E}_1\mathcal{E}_2 \sin(\phi_1 - \phi_2) = \mathcal{E}_0^2 \sin(2\beta). \quad (2.25d)$$

Equation 2.25 can be further manipulated to give

$$\sqrt{I} = \mathcal{E}_0 \quad (2.26a)$$

$$\frac{V}{I} = \sin(2\beta) \quad (2.26b)$$

$$\frac{U}{Q} = \tan(2\chi). \quad (2.26c)$$

This shows that the three parameters needed to describe pure elliptical polarisation completely are $\mathcal{E}_0$, β , and χ . The four Stokes parameters are related to each other via the equation

$$I^2 = Q^2 + U^2 + V^2. \quad (2.27)$$

The meanings of the Stokes parameters will now be explained. I is proportional to the energy flux or total intensity of the wave. V is a circularity parameter that measures the ratio of the principal axes. The wave has right or left polarisation if V is positive or negative and the wave is linearly polarised if $V = 0$. The only other independent parameter, either Q or U describes the orientation of the ellipse with respect to the x axis. Together they are used to determine the linear polarisation angle χ using Equation 2.26c. The case where $Q = U = 0$ is the condition for pure circular polarisation.

We can rewrite the Stokes parameters as defined by Conway & Kronberg (1969). First, we need to specify the axes as shown in Figure 2.5 with A and B orientated north and east and the C and D axes rotated 45 degrees with respect to the A and B axes. The position angle χ in increases north through east. Updated according to IAU conventions those relations are

$$I = \langle E_A^2 \rangle + \langle E_B^2 \rangle = \langle E_C^2 \rangle + \langle E_D^2 \rangle = \langle E_R^2 \rangle + \langle E_L^2 \rangle \quad (2.28a)$$

$$Q = \langle E_A^2 \rangle - \langle E_B^2 \rangle \quad (2.28b)$$

$$U = \langle E_C^2 \rangle - \langle E_D^2 \rangle \quad (2.28c)$$

$$V = \langle E_R^2 \rangle - \langle E_L^2 \rangle. \quad (2.28d)$$

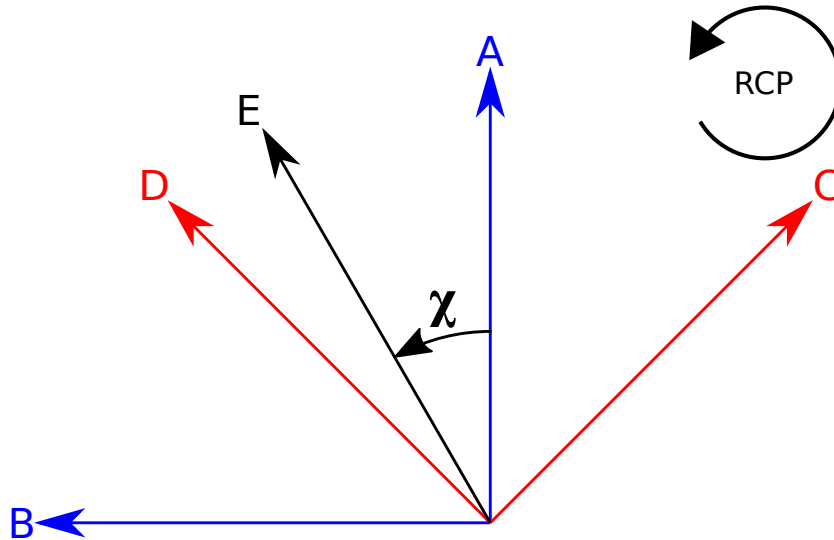


Figure 2.5: Axes defining the Stokes parameters Q , U and V . Diagram adapted from Conway & Kronberg (1969). For illustrative purposes, the angle χ is increasing from North through East to an arbitrary point labeled E .

Now consider a polarised component to the radiation E_{pol} and an unpolarised component E_{unpol}

$$E_A = \frac{E_{unpol}}{\sqrt{2}} + E_{pol} \cos \chi \quad (2.29a)$$

$$E_B = \frac{E_{unpol}}{\sqrt{2}} + E_{pol} \sin \chi \quad (2.29b)$$

$$E_C = \frac{E_{unpol}}{\sqrt{2}} + E_{pol} \sin(45^\circ - \chi) \quad (2.29c)$$

$$E_D = \frac{E_{unpol}}{\sqrt{2}} + E_{pol} \cos(45^\circ - \chi). \quad (2.29d)$$

We can use Equations 2.28 and 2.29 to calculate the Stokes Q and U parameters

$$Q = \langle E_{pol}^2 \rangle \cos(2\chi), \quad (2.30)$$

and

$$U = \langle E_{pol}^2 \rangle \sin(2\chi). \quad (2.31)$$

The $\langle E_{unpol} E_{pol} \rangle$ terms vanish as the polarised and unpolarised components are uncorrelated. Again we see that the polarisation angle χ is given by $\tan 2\chi = \frac{U}{Q}$ and the total linearly polarised intensity by $E_{pol}^2 = Q^2 + U^2$. Hence, we can construct a complex quantity called the complex polarised flux $\mathbf{P}$

$$\mathbf{P} = Q + iU = mIe^{2i\chi}. \quad (2.32)$$

On the complex coordinate plane, $\mathbf{P}$ will be a vector with amplitude mI (where m is the fractional polarisation) and phase 2χ . We can connect these parameters to the output of a radio telescope's correlator which have RCP and LCP feeds. Between the two feeds the following four correlations are possible

$$\langle LL^*(u, v) \rangle \quad (2.33a)$$

$$\langle LR^*(u, v) \rangle \quad (2.33b)$$

$$\langle RL^*(u, v) \rangle \quad (2.33c)$$

$$\langle RR^*(u, v) \rangle, \quad (2.33d)$$

where R and L refer to the right and left polarised output of a single antenna in response to incoming radiation. For example, in a two-element baseline pair $\langle LR^*(u, v) \rangle$ would mean the correlation of the LCP radiation of one baseline element to the RCP radiation of the other telescope. Comparison shows that the correlations

$\langle LL^* (u, v) \rangle$ and $\langle RR^* (u, v) \rangle$ are analogous to $2E_L^2$ and $2E_R^2$ in Equation 2.28. Solving for $\langle LL^* (u, v) \rangle$ and $\langle RR^* (u, v) \rangle$ using Equations 2.28a and 2.28d yields

$$\langle LL^* (u, v) \rangle = I - V \quad (2.34a)$$

$$\langle RR^* (u, v) \rangle = I + V. \quad (2.34b)$$

This demonstrates that the quantities $\langle LL^* (u, v) \rangle$ and $\langle RR^* (u, v) \rangle$ only contain information about the total intensity and circular polarisation. Hence we need the $\langle LR^* (u, v) \rangle$ and $\langle RL^* (u, v) \rangle$ correlations in order to calculate Stokes Q and U . This is achieved by writing the electric field components E_A and E_B in terms of the circular components E_R and E_L

$$E_A = E_R \cos \omega t + E_L \sin \omega t \quad (2.35a)$$

$$E_B = E_R \sin \omega t - E_L \cos \omega t. \quad (2.35b)$$

Writing this in complex form with $\chi = 0$ meaning both circular components are in phase with each other and point North at $t = 0$, then we can say

$$E_A = (E_R + E_L) e^{i\omega t} \quad (2.36a)$$

$$E_B = -i(E_R - E_L) e^{i\omega t}, \quad (2.36b)$$

where the real parts of this equation give 2.35. Now rearranging to express E_R and E_L in terms of E_A and E_B we can express

$$E_R = \frac{1}{2} (E_A + iE_B) e^{-i\omega t} \quad (2.37a)$$

$$E_L = \frac{1}{2} (E_A - iE_B) e^{-i\omega t}. \quad (2.37b)$$

Using Equation 2.37 we can write the correlation of R and L in terms of the linearly polarised components

$$\langle RL^* (u, v) \rangle = 2 \langle E_R E_L^* \rangle \quad (2.38a)$$

$$= \frac{1}{2} (E_A + iE_B) (E_A + iE_B) \quad (2.38b)$$

$$= Q + iE_A E_B, \quad (2.38c)$$

where, referring back to Equation 2.28, $\frac{1}{2} (E_A^2 - E_B^2) = \langle E_A^2 \rangle - \langle E_B^2 \rangle = Q$. In Equation 2.25c in the case of $\chi = 0$, we are left with $U = 2\mathcal{E}_1 \mathcal{E}_2$ which in terms of E_A

and E_B gives

$$U = 2 \langle E_A E_B \rangle = E_A E_B. \quad (2.39)$$

Substituting this into Equation 2.38c gives us

$$\langle RL^* (u, v) \rangle = Q + iU. \quad (2.40)$$

Similarly, it can be shown that $\langle LR^* (u, v) \rangle = Q - iU$. In summary, there are four possible correlations

$$\langle LL^* (u, v) \rangle = I - V \quad (2.41a)$$

$$\langle LR^* (u, v) \rangle = Q - iU \quad (2.41b)$$

$$\langle RL^* (u, v) \rangle = Q + iU \quad (2.41c)$$

$$\langle RR^* (u, v) \rangle = I + V. \quad (2.41d)$$

Thus the four correlations can be used to give all the Stokes parameters and polarisation information. These raw correlations as initially recorded will not be entirely accurate due to instrumental effects. This will be discussed in Section 2.4.

2.4 Calibration

2.4.1 Calibration Formalism

This subsection is based on Fomalont & Perley (1999). The raw data obtained from the telescope array are referred to as the observed visibilities $\widetilde{V}_{ij}(t)$. This differs from the true visibilities $V_{ij}(t)$ due to a variety of atmospheric and instrumental effects. The aim of calibration is to recover the true visibilities before the data are used. The basic calibration formula can be written as

$$\widetilde{V}_{ij}(t) = G_{ij}(t) V_{ij}(t) + \epsilon_{ij}(t) + \eta_{ij}(t), \quad (2.42)$$

where t is the time of observation, $G_{ij}(t)$ is the complex baseline-based gain, $\epsilon_{ij}(t)$ is the baseline-based complex offset, and $\eta_{ij}(t)$ is the stochastic complex noise. As most data corruption occurs before correlation, we can approximate the complex gain $G_{ij}(t)$ (which we need to find) as the product of two antenna-based complex gains

$$G_{ij}(t) = g_i(t) g_j^*(t) = a_i(t) a_j^*(t) e^{i(\phi_i(t) - \phi_j(t))}, \quad (2.43)$$

where $a_i(t)$ is an antenna based amplitude correction and $\phi_i(t)$ is an antenna-based phase correction. In an array of N antennas there are N values of $g_i(t)$ that need to be solved for and correspondingly $N(N-1)$ values of $G_{ij}(t)$. The following section will outline the methods of calibration. Throughout my thesis calibration was done using the Astronomical Image Processing System (AIPS).

2.4.2 Initial Calibration

2.4.2.1 Amplitude Calibration

This subsection is based on Walker (1999). The power of signals received by a telescope can be defined in terms of an equivalent temperature T . Using the Rayleigh-Jeans approximation to the Planck radiation law for a blackbody, the power P is given by

$$P = k_B T \Delta\nu, \quad (2.44)$$

where k_B is the Boltzmann's constant and $\Delta\nu$ is the observing bandwidth. The total system temperature T_{sys} is made up of contributions $T_{sys} = T_a + T_{noise}$ where T_a is the antenna temperature and T_{noise} represents noise added to the system. The noise temperature contains contributions from the receiver noise, feed losses, spillover, and atmospheric emission.

Initially, the raw correlation coefficients are in arbitrary units but need to be converted into physical flux densities in the units of Janskys (Jy). This is done by finding the system equivalent flux density (SEFD), which is defined as the flux density of a source that would contribute the same power as that due to the system noise. It is necessary in amplitude calibration to estimate antenna SEFD values as functions of time, elevation and frequency, and applying the calculated corrections to the raw correlation coefficients to obtain V_{ij} . In units of Janskys (Jy), the correlated flux on a particular baseline is defined as

$$S_{ij} = \delta_{ij} \sqrt{\frac{T_{sys,i} T_{sys,j}}{g_i g_j}}, \quad (2.45)$$

where S_{ij} is the correlated flux on the baseline between antenna i and j , δ_{ij} is the correlation coefficient between the two antennas, and g_i is the antenna gain of the i th antenna. Antenna gains (units of K Jy^{-1}) are expressed as a peak gain multiplied by a normalized "gain curve" which is a function of the antenna elevation angle. Assuming the antenna gain curve is already known, we can calculate the flux in

Equation 2.45. In AIPS Equation 2.45 is calculated using the task APCAL.

2.4.2.2 Phase Calibration

Firstly, the effect of the parallactic angle needs to be removed. The parallactic angle is the angle formed at a celestial object by the intersection of arcs drawn on the celestial sphere to the observer's zenith and to the celestial pole. The radio telescopes in most arrays have altitude-azimuth (or alt-az) mounts. This mount is limited to vertical and horizontal rotation. Altitude is the angle between the observer's local horizon and the celestial object. Azimuth refers to the angle between true North and the celestial body, increasing eastward around the observer's horizon. The parallactic angle describes the correctional rotation of the feeds of an alt-az telescope as it tracks a source throughout an observation, needed to keep a constant orientation. Each antenna is at a different location in the array and so has a different parallactic angle, introducing an additional phase term to the visibilities which needs to be removed. This is done in AIPS using the task CLCOR.

Secondly, the instrumental phases and delays need to be corrected. These are caused by the passage of signals through cables and electronic systems and can cause phase jumps between spectral windows. Correction is done using the procedure VLBPAPCOR over a short timescale. VLBPAPCOR makes use of the pulse calibration system which consists of pulses injected into the signal path at the receivers. These pulses act to define the delay reference point for astrometry.

After correlation and pulse calibration, the VLBI data may still exhibit small phase errors. These manifest as slopes in phase as a function of time or frequency. This needs to be corrected so that the two signals phase up appropriately. The process of finding these delays both in time and in frequency is called fringe fitting.

Following the treatment by Cotton (1995), the interferometer phase is related to the geometrical delay by the relationship

$$\phi_{t,\nu} = 2\pi\nu\tau_g, \quad (2.46)$$

where $\phi_{t,\nu}$ is the interferometer phase, ν is the frequency and τ_g is the geometrical delay. Differentiating Equation 2.46 shows how interferometer phase errors and the geometrical delay are related

$$d\phi_{t,\nu} = 2\pi\nu d\tau_g. \quad (2.47)$$

Thus, correlator delay errors will result in time and frequency dependent errors in

$\phi_{t,v}$. Taking a first order linear expansion of Equation 2.47 yields

$$\Delta\phi_{t,v} = \phi_0 + \frac{\partial\phi}{\partial\nu}\Delta\nu + \frac{\partial\phi}{\partial t}\Delta t, \quad (2.48)$$

where ϕ_0 is the phase error at the reference time, $\frac{\partial\phi}{\partial\nu}$ is the delay residual and $\frac{\partial\phi}{\partial t}$ is the rate residual. These are the quantities that need to be corrected for. Most sources of delay error can be separated into contributions from individual antennas. Hence, baseline errors can be considered to be differences between antenna errors. The phase errors between antennas i and j can be expressed as

$$\Delta\phi_{ij} = \phi_{i0} - \phi_{j0} + \left(\left[\frac{\partial\phi_i}{\partial\nu} - \frac{\partial\phi_j}{\partial\nu} \right] \Delta\nu + \left[\frac{\partial\phi_i}{\partial t} - \frac{\partial\phi_j}{\partial t} \right] \Delta t \right). \quad (2.49)$$

Throughout my thesis, "global" fringe fitting is utilized (see Schwab & Cotton (1983)) which calculates simultaneous solutions for all the delay and rate parameters for all antennas involved using Equation 2.49. In AIPS, following instrumental corrections, global fringe fitting is done using the task FRING. This removes frequency and time-dependent phase errors over the complete time range. The procedure VLBA POL (which includes FRING) is then used to remove cross-polarisation delays.

2.4.3 Self-Calibration

This subsection is based on Cornwell & Fomalont (1989). The sensitivity achieved after the initial amplitude and phase calibration is limited due to residual calibration errors in the visibility data. However, many objects have enough signal-to-noise (S/N) that they can be used to calibrate themselves to obtain a better image. This is called self-calibration. It is an iterative process. The procedure in self-calibration is to use a least-mean-squares method to calculate the gains $g(t)$ that minimize the square of the modulus of the difference between the observed visibilities $\tilde{V}$ and the corresponding values of a derived visibility model V^{model}

$$S = \sum_k \sum_{\substack{i,j \\ i \neq j}} w_{ij}(t_k) \left| \tilde{V}_{ij}(t_k) - g_i(t_k) g_j^*(t_k) V_{ij}^{model}(t_k) \right|^2. \quad (2.50)$$

An image model made with the CLEAN algorithm described in Section 2.2 is Fourier transformed to make this visibility model. Once calculated, the estimated inverse gain terms are applied to the measured visibilities to create improved visibilities. The CLEAN algorithm is run again to obtain a new image model of the source and the process is repeated multiple times until convergence. With each iteration, there is a

slight improvement to the signal-to-noise ratio which allows for a deeper CLEAN and a better model. In creating this model, care must be taken only to include real emission. The weighting coefficient w_{ij} is usually chosen to be inversely proportional to the variance of $\tilde{V}_{ij}$, and the quantities described are all functions of time within the observing period.

In AIPS, the model V^{model} consisting of a collection of point sources is constructed from the observed visibilities $\tilde{V}$ using the task IMAGR. If necessary, this model can then be manually edited using the task CCEDT to include only the clean components associated with real emission. The calibration is calculated and applied to the original visibilities using the task CALIB to create a new set of improved visibilities.

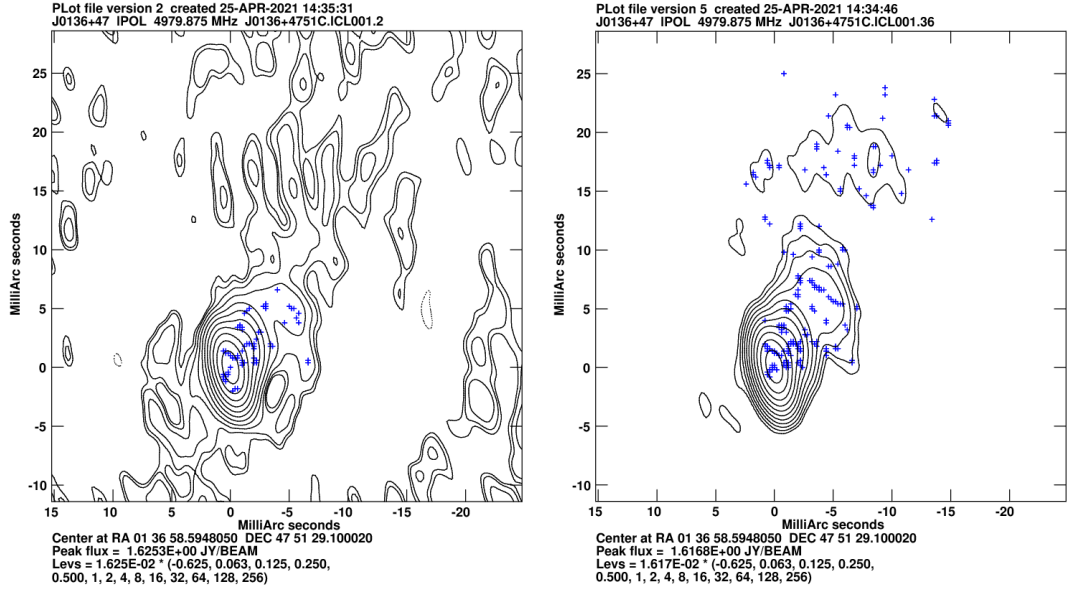


Figure 2.6: Comparison of intensity distribution for J0136+4751, before (left) and after (right) numerous iterations of self-calibration. This shows how effective the algorithm is at reducing noise. The blue crosses are "CLEAN components".

2.4.4 Polarisation Calibration

Ideally, the two feeds of a radio telescope should measure RCP and LCP emission separately. However in reality there is "leakage" and both feeds detect a small amount of the other term. Following the formalism in Conway & Kronberg (1969), the complex voltages can be written as

$$v_L = G_L \left[E_L e^{i\phi_p} + D_L E_R e^{-i\phi_p} \right] \equiv L \quad (2.51a)$$

$$v_R = G_R \left[E_R e^{-i\phi_p} + D_R E_L e^{i\phi_p} \right] \equiv R, \quad (2.51b)$$

where G refers to the complex gain factors determined in calibration, E is the induced electric fields in complex notation. The angle ϕ_p is the parallactic angle for a particular telescope that changes in time. The D factors represent the polarisation "leakage" explained earlier and are referred to as the instrumental polarisations, polarisation cross gains, or D-terms. The D-terms are expected to be roughly 1–10% and therefore we will ignore any second or higher-order products involving the D-terms as well any D-terms involving $E_L E_R^*$ or $E_R E_L^*$. The correlator output is then

$$L_1 L_2^* = G_{L1} G_{L2}^* E_{L1} E_{L2}^* e^{i(\phi_{p1} - \phi_{p2})} \quad (2.52a)$$

$$R_1 R_2^* = G_{R1} G_{R2}^* E_{R1} E_{R2}^* e^{-i(\phi_{p1} - \phi_{p2})} \quad (2.52b)$$

$$R_1 L_2^* = G_{R1} G_{L2}^* \left[E_{R1} E_{L2}^* e^{-i(\phi_{p1} + \phi_{p2})} + D_{L2}^* E_{R1} E_{R2}^* e^{-i(\phi_{p1} - \phi_{p2})} + D_{R1} E_{L1} E_{L2}^* e^{i(\phi_{p1} - \phi_{p2})} \right] \quad (2.52c)$$

$$L_1 R_2^* = G_{L1} G_{R2}^* \left[E_{L1} E_{R2}^* e^{i(\phi_{p1} + \phi_{p2})} + D_{R2}^* E_{L1} E_{L2}^* e^{i(\phi_{p1} - \phi_{p2})} + D_{L1} E_{R1} E_{R2}^* e^{-i(\phi_{p1} - \phi_{p2})} \right], \quad (2.52d)$$

where $L_1 R_2^*$ refers to a correlation between the LCP of antenna 1 and the RCP of antenna 2 etc. This can be simplified by expressing it in terms of Stokes parameters assuming that $V \approx 0$

$$L_1 L_2^* = G_{L1} G_{L2}^* I e^{i(\phi_{p1} - \phi_{p2})} \quad (2.53a)$$

$$R_1 R_2^* = G_{R1} G_{R2}^* I e^{-i(\phi_{p1} - \phi_{p2})} \quad (2.53b)$$

$$R_1 L_2^* = G_{R1} G_{L2}^* \left[P e^{-i(\phi_{p1} + \phi_{p2})} + I \left(D_{L2}^* e^{-i(\phi_{p1} - \phi_{p2})} + D_{R1} e^{i(\phi_{p1} - \phi_{p2})} \right) \right] \quad (2.53c)$$

$$L_1 R_2^* = G_{L1} G_{R2}^* \left[P^* e^{i(\phi_{p1} + \phi_{p2})} + I \left(D_{R2}^* e^{i(\phi_{p1} - \phi_{p2})} + D_{L1} e^{-i(\phi_{p1} - \phi_{p2})} \right) \right]. \quad (2.53d)$$

The parallactic angle factors can then be added in such a way as to remove the parallactic angle dependence from the LL and RR correlations

$$L_1 L_2^* = G_{L1} G_{L2}^* I \quad (2.54a)$$

$$R_1 R_2^* = G_{R1} G_{R2}^* I \quad (2.54b)$$

$$R_1 L_2^* = G_{R1} G_{L2}^* \left[P + I \left(D_{L2}^* e^{i2\phi_{p2}} + D_{R1} e^{i2\phi_{p1}} \right) \right] \quad (2.54c)$$

$$L_1 R_2^* = G_{L1} G_{R2}^* \left[P^* + I \left(D_{R2}^* e^{-i2\phi_{p2}} + D_{L1} e^{-i2\phi_{p1}} \right) \right]. \quad (2.54d)$$

With this, the three terms in the RL and LR correlations have different dependence on the parallactic angle. This means that the D-terms can be calculated by obtaining a series of observations of a calibrator source that is either unpolarised or has a simple polarisation structure and spans a large range of parallactic angles. The D-terms are constant on the typical time scales of a VLBI experiment and once

calculated, the D-terms can be removed from the data. In a multisource experiment, a single D-Term "calibrator" source is used to carry out polarisation calibration over the entire experiment. A suitable calibrator has an intermediate declination, large parallactic angle coverage, and a sufficiently high number of visibilities. The AIPS task LPCAL is then used to calculate the D-Terms.

The LPCAL algorithm (Leppanen et al. 1995) models the calibrator source polarisation parametrically (see also Martí-Vidal et al. (2021) and The Event Horizon Telescope Collaboration (2021)). The total-intensity brightness distribution, I , is divided in a set of disjoint of N regions (or "polarisation sub-components"), I_n , such that

$$I = \sum_{n=1}^N I_n. \quad (2.55)$$

It is assumed that the fractional polarisation, and EVPA of the source is constant across each sub-component. This implies that

$$Q = \sum_{n=1}^N q_n I_n \quad (2.56a)$$

$$\mathcal{U} = \sum_{n=1}^N u_n I_n, \quad (2.56b)$$

where q_n and u_n are real-valued and constant. This condition is known as the "similarity approximation". Beforehand, the source intensity structure undergoes self-calibration (See Section 2.4.3). The LPCAL algorithm estimates the parameters q_n , u_n , D_R , and D_L of all the antennas which minimizes the difference between the calibrated cross-polarisation visibilities (from Equation 2.54) and the Fourier transformed model brightness by using a least-squares minimization of the error function given by

$$\chi^2 = \sum_{m=1} w_m \left| RL_{ij,m}^* - (\tilde{Q} + i\tilde{\mathcal{U}})_m \right|^2 + \sum_{m=1} w_m \left| LR_{ij,m}^* - (\tilde{Q} - i\tilde{\mathcal{U}})_m \right|^2, \quad (2.57)$$

where w_m is the weight of the m th visibility, the subscripts i, j refer to an antenna pair and $\tilde{Q}$ and $\tilde{\mathcal{U}}$ are the Fourier transforms of the model Stokes parameters. The total number of parameters used in this fit is equal to twice the number of source sub-components, which correspond to q_n and u_n in Equation 2.56 plus four times the number of antennas (corresponding to the real and imaginary parts of the D_R and D_L of each antenna). Due to the parallactic angle coverage, it is possible to decouple the D-terms from the source polarisation parameters. This means that the more complete the parallactic angle coverage, the more accurate the derived

D-terms will be.

2.5 Reliability of Rotation Measure Gradients

In order to characterize the errors in a calculated rotation measure map let us examine the calculation process in more detail. Recall Equation 2.26c, the way we measure the polarisation angle χ

$$\chi = \frac{1}{2} \arctan\left(\frac{U}{Q}\right). \quad (2.58)$$

Knowing this, it is clear any error in χ , namely σ_χ , will depend on errors in Q and U , which we will refer to as σ_Q and σ_U . In error analysis, if a calculated result y is a function of measured parameters $\{x_1, x_2, \dots, x_n\}$, each of which has an uncertainty $\{\Delta x_1, \Delta x_2, \dots, \Delta x_n\}$ then the uncertainty in y can be calculated by

$$\Delta y = \sqrt{\sum_{i=1}^n \left(\frac{\partial y}{\partial x_i} \Delta x_i \right)^2}. \quad (2.59)$$

Using Equation 2.59 this would mean our error in χ is

$$\sigma_\chi^2 = \left(\frac{\partial \chi}{\partial Q} \sigma_Q \right)^2 + \left(\frac{\partial \chi}{\partial U} \sigma_U \right)^2. \quad (2.60)$$

Calculating the partial derivatives we get

$$\frac{\partial \chi}{\partial Q} = -\frac{1}{2} \frac{U}{Q^2 + U^2} \quad (2.61a)$$

$$\frac{\partial \chi}{\partial U} = \frac{1}{2} \frac{Q}{Q^2 + U^2}, \quad (2.61b)$$

Substituting this back into Equation 2.60 gives

$$\sigma_\chi^2 = \frac{U^2 \sigma_Q^2 + Q^2 \sigma_U^2}{4(Q^2 + U^2)^2}, \quad (2.62)$$

which gives a method to estimate the error in the polarisation angle. Based on Monte Carlo simulations of VLBI observations with snapshot (u, v) coverage, Hovatta et al. (2012) concludes the errors σ_Q and σ_U are estimated well by the equation

$$\sigma = \sqrt{\sigma_{rms}^2 + \sigma_{Dterm}^2 + (1.5 \times \sigma_{rms})^2}, \quad (2.63)$$

where σ_{rms} is the corresponding background rms. The additional error σ_{Dterm} results from the presence of residual instrumental polarisations in the data following D-term calibration. It is defined as

$$\sigma_{Dterm} = \frac{\sigma_{\Delta}}{\sqrt{N_{ant} \times N_{IF} \times N_{scan}}} \sqrt{I^2 + (0.3 \times I_{peak})^2}, \quad (2.64)$$

where σ_{Δ} is the estimated uncertainty in the individual D-terms, N_{ant} is the number of antennas in the array, N_{IF} is the number of intermediate frequencies (IFs), N_{scan} is the number of scans with independent parallactic angles, I is the total intensity at the location in question, and I_{peak} is the map's peak total intensity (Roberts et al. 1994). The effect of σ_{Dterm} is largest for sources with the highest I_{peak} . From Table A.1, the observed source from this study with the highest I_{peak} is J0854+2006 at 5 GHz. In this case, considering I at the fourth contour level where the edge RM values are located and taking $\sigma_{\Delta} = 0.002$ from the scatter of the D-terms in the data of Hovatta et al. (2012) this gives

$$\sigma_{Dterm} = \frac{0.002}{\sqrt{10 \times 8 \times 10}} \sqrt{(0.02)^2 + (0.3 \times 4.258)^2} \quad (2.65a)$$

$$\sigma_{Dterm} = 0.09 \text{ mJy/beam} \quad (2.65b)$$

$$\sigma_{Dterm} = 0.2\sigma_{rms}. \quad (2.65c)$$

This shows that σ_{Dterm} can be taken to be negligible compared to σ_{rms} for all sources in the calculation of Equation 2.63. Neglecting σ_{Dterm} , we used the error estimates $\sigma_Q = 1.8\sigma_{rms,Q}$ and $\sigma_U = 1.8\sigma_{rms,U}$ where $\sigma_{rms,Q}$ and $\sigma_{rms,U}$ is the background rms of the Q and U maps respectively. Once derived, the resulting χ , σ_{χ} , and λ^2 are used in a weighted linear fit to solve for Equation 1.49 and calculate the RM. In general, for a weighted linear fit, a line of the form $f(x) = ax + b$ is fitted to a set of n data points $\{x_1, x_2, \dots, x_n\}$ and $\{y_1, y_2, \dots, y_n\}$ with associated y errors $\{\sigma_1, \sigma_2, \dots, \sigma_n\}$. The slope a of this will be the RM and the intercept on the y axis b will correspond to the intrinsic polarisation angle χ_0 . These results are found by minimizing the quantity

$$\chi^2 = \sum_{i=1}^n w_i (y_i - ax_i + b). \quad (2.66)$$

The reduced chi-squared statistic χ should not be confused with the polarisation angle. The values $w_i = \frac{1}{\sigma_i^2}$ are the statistical weights calculated from the y errors. The

end result of this fit are the relations

$$a = \frac{\sum x_i w_i \sum y_i w_i - \sum x_i y_i w_i \sum w_i}{(\sum x_i w_i)^2 - \sum x_i^2 w_i \sum w_i} = \text{RM} \quad (2.67a)$$

$$b = \frac{\sum x_i y_i w_i - a \sum x_i^2 w_i}{\sum x_i w_i} = \chi_0. \quad (2.67b)$$

The uncertainties in this fit are

$$\sigma_a = \sqrt{\frac{\sum w_i}{(\sum x_i w_i)^2 - \sum x_i^2 w_i \sum w_i}} = \sigma_{\text{RM}} \quad (2.68a)$$

$$\sigma_b = \sqrt{\frac{\sum x_i^2 w_i}{\sum x_i^2 \sum w_i - (\sum x_i w_i)^2}} = \sigma_{\chi_0}. \quad (2.68b)$$

Note, however, in measuring polarisation angle, there are ambiguities of $n\pi$ radians (i.e. multiples of 180°). In finding the reduced chi-squared statistic, adjustments of $\pm n\pi$ may be needed to be added to the angles of frequencies for a better fit. Usually, angular shifts of only $\pm\pi$ or $\pm 2\pi$ are needed. This may mistakenly lead to artificially high or low values of RM. The smoothness and plausibility of both the RM and χ_0 map must be considered to ensure the right shifts.

When taking a rotation measure gradient across a source, the statistical significance of the transverse RM gradient is defined as the magnitude of the difference between the RMs at the two ends of the gradient divided by the uncertainty in this difference. The uncertainty is taken to be the sum of the individual RM uncertainties added in quadrature

$$\text{significance}(\sigma) = \frac{|\text{RM}_1 - \text{RM}_2|}{\sqrt{\sigma_{\text{RM}_1}^2 + \sigma_{\text{RM}_2}^2}}, \quad (2.69)$$

where RM_1 and RM_2 are the start and end rotation measures of a slice from Equation 2.67a and σ_{RM_1} and σ_{RM_2} are the related errors from Equation 2.68a. A transverse RM gradient with a statistical significance of at least 3σ is considered evidence of a real transverse RM gradient. It is important that a check is made to ensure that tentative transverse RM gradients are monotonic within the errors. Sometimes, very localized regions with large formal significances may arise due to the RM values in edge pixels with low signal-to-noise ratios; in most cases, these can be taken to be spurious. Thus, reliable transverse RM gradients will have significances of at least 3σ , be monotonic within the errors, and be present all across the jet, not just in a few edge pixels. Extended regions of transverse RM gradients along the jet with significances of $2-3\sigma$ may also be real.

Chapter 3

Results

3.1 Introduction

The observations presented here were made with the VLBA (shown in Figure 3.1) in July to September 2017 (BG246) and March 2019 (BG258). The experiments in which each source was observed are shown in Table 3.1 and their respective observation dates in Table 3.2. The BG246 observations had to be observed in "filler" mode, in which schedules sitting in a dynamical scheduling queue are observed when a suitable gap appears in the schedule for more highly rated projects. For this reason, the BG246 observations (a total of about 190 AGNs) were divided up into a large number of short schedules. Each source was observed in three schedules: one with six 115 second scans spread out around the source's zenith, one with two to three 115 second scans as the source is rising toward the zenith, and one with two to three 115 second scans as the source is descending from the zenith. We had no control over when these individual observations were made, but in practice, of the total of 21 sets of three observations, 9 were all observed within 40 days and another 6 were observed within 70 days. The remaining sets of three observations that ended up being made over an unacceptably large time range (150–210 days) were re-observed as individual 12 hour runs with the same total observing time in BG258. The time range spanned by the three BG246 experiments comprising a single set of observations is given in Table 3.1. The uv coverages obtained after combining the three BG246 datasets for a low-declination and a high-declination source are shown as examples in Figure 3.2.



Figure 3.1: Figure showing the ten telescopes of the Very Long Baseline Array (VLBA). Image Credit: NASA's Goddard Space Flight Center.

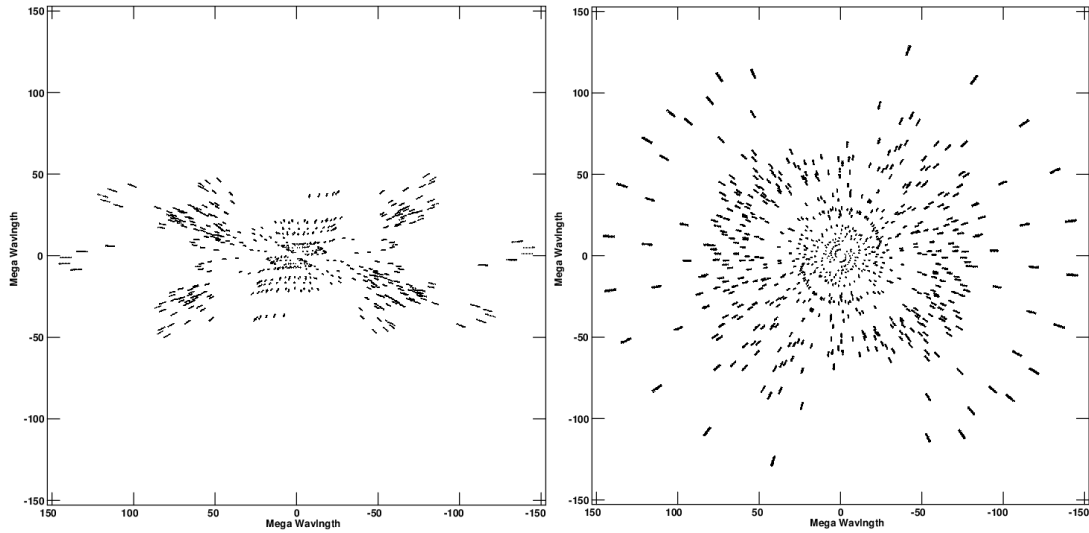


Figure 3.2: The total C band uv coverage obtained for sources J0006-0632 (left) and J0958+6533 (right).

The observations were carried out simultaneously in the C, S, and L radio bands. The L band is split up into 2 sections referred to as L1 (1.45 GHz) and L2 (1.8 GHz). Hence, the observations consist of data at 4 frequencies: 5, 2.2, 1.8, and 1.45 GHz. Alternatively, this can be expressed in wavelengths as 6, 13, 17, and 21 cm. The C and S band data were built up of eight intermediate frequencies (IFs) while the L1 and L2 data were each made up of four. A summary of the total frequency ranges used for each band is given in Table 3.3. Initial calibration and D-Term calibration were done in AIPS for each experiment using the techniques discussed in Section 2.4.2.

Table 3.1: Experiments for each source. The majority of sources consist of three BG246 experiments observed at different epochs which were concatenated together while the BG258 sources were at a single date.

Source	Experiments	Total Time Span
J0006-0623	BG246A, BG246V, BG246AP	66 days
J0050-0929	BG246D, BG246Y, BG246AP	51 days
J0121+1149	BG246D, BG246Y, BG246AP	51 days
J0721+7120	BG246I, BG246V, BG246AD	15 days
J0738+1742	BG246I, BG246V, BG246AD	15 days
J0748+2400	BG246J, BG246X, BG246AE	17 days
J0818+4222	BG246K, BG246AB, BG246AO	30 days
J0825+0309	BG246J, BG246X, BG246AE	17 days
J0854+2006	BG246K, BG246AB, BG246AO	30 days
J0958+6533	BG246L, BG246Y, BG246AF	31 days
J1751+0939	BG258D	12 hours
J1800+7828	BG258E	12 hours
J1806+6949	BG258E	12 hours
J1824+5651	BG258D	12 hours
J2005+7752	BG258E	12 hours
J2202+4216	BG246A, BG246V, BG246AP	66 days

Table 3.2: Observation dates and missing antennas for the experiments in Table 3.1.

Experiment	Observation Date	Missing Antennas
BG246A	06/07/2017	North Liberty
BG246D	03/08/2017	Fort Davis
BG246I	11/08/2017	None
BG246J	24/07/2017	None
BG246K	25/07/2017	None
BG246L	11/07/2017	Fort Davis
BG246V	27/07/2017	Fort Davis
BG246X	10/08/2017	None
BG246Y	21/07/2017	None
BG246AB	22/07/2017	None
BG246AD	27/07/2017	Fort Davis
BG246AE	04/08/2017	None
BG246AF	11/08/2017	None
BG246AO	24/08/2017	Kitt Peak, Hancock
BG246AP	10/09/2017	St. Croix
BG258D	12/03/2019	None
BG258E	29/03/2019	Hancock

Table 3.3: Full range frequencies of the bands used. The width of each intermediate frequency is 32 MHz with a channel separation of 500 kHz.

IF	C band	S band	L2 band	L1 band
1	4.852 GHz	2.156 GHz	1.744 GHz	1.392 GHz
2	4.884 GHz	2.188 GHz	1.776 GHz	1.424 GHz
3	4.916 GHz	2.22 GHz	1.808 GHz	1.456 GHz
4	4.948 GHz	2.252 GHz	1.84 GHz	1.488 GHz
5	4.98 GHz	2.284 GHz	-	-
6	5.012 GHz	2.316 GHz	-	-
7	5.044 GHz	2.348 GHz	-	-
8	5.076 GHz	2.38 GHz	-	-

Self-calibration on each target source was done by myself in AIPS using the techniques in Section 2.4.3. Following this, the Stokes I , Q , and U data were exported from AIPS to the FITS file format using the task FITTP for use in the software package CASA. Fractional polarisation, polarisation angle, and spectral index maps were made using the CASA task immath. Rotation Measure maps were made using code developed by Dr. Eoin Murphy (RM_code.py) which takes the Stokes Q and U maps as inputs. Plots of the estimated significances of the difference of the RM values on either side of the jet (sigma plots) were made using another code (sigma_checker.py) which is a modified version of RM_code.py. This code takes the inputted maps and rotates them such that the jet direction is horizontal and to the right. The statistical significance across the jet is calculated by using Equation 2.69 on the start and endpoints of a vertical slice.

As discussed in Section 1.4, the maps at different frequencies need to be shifted to prevent misalignment. This was using achieved the code developed by Sarah Croke (Croke & Gabuzda 2008) which uses cross-correlation of intensity maps convolved with matched restoring beam parameters. For the sources discussed here, the shifts were derived relative to the C band intensity image, which remains unshifted. To check for consistency, a comparison was made between the derived shifts for each source and previously published MOJAVE shifts at higher frequencies of Pushkarev et al. (2012). Another criterion for correct image alignment was that the resulting spectral index maps displayed the expected distribution for a partially optically thick core and optically thin jet. The spectral index is expected to decrease monotonically from the core along the direction of the inner jet. A summary of the applied shifts is shown in Table 3.4 Faraday rotation occurs when source radiation passes through magnetized plasma in the source as well as our own Galaxy. I refer to this as the Galactic rotation measure or RM_{Gal} . When plotting the EVPAs and Faraday rotation

Table 3.4: Shifts (dRA, dDec.) applied to each source. Positive shifts correspond to moving the image downward (to the south) and to the left-hand side (east) relative to the C band image.

Source	Cellsize (mas/pixel)	C-S Shift (mas)	C-L2 Shift (mas)	C-L1 Shift (mas)
J0006-0623	0.2	(−0.4, −0.2)	(−1.2, −0.4)	(−1.2, −0.4)
J0050-0929	0.2	(−0.2, −0.8)	(−0.2, −1.2)	(−0.4, −1.6)
J0121+1149	0.2	(0,0)	(0,0)	(0,0)
J0721+7120	0.2	(0, −0.2)	(0, −0.2)	(0, −0.4)
J0738+1742	0.2	(0.4, −0.2)	(0.6, −0.2)	(0.8, −0.2)
J0748+2400	0.2	(−0.2, −0.4)	(−0.2, −0.4)	(−0.4, −0.6)
J0818+4222	0.2	(0.2, 0)	(0.4, 0)	(0.4, 0)
J0825+0309	0.2	(0.2, −0.4)	(0.4, −0.8)	(0.6, −1)
J0854+2006	0.2	(0, 0)	(−0.2, 0)	(−0.2, 0)
J0958+6533	0.2	(−0.2, 0)	(−0.4, −0.2)	(−0.4, −0.2)
J1751+0939	0.2	(0, 0)	(0, 0)	(0, 0)
J1800+7828	0.3	(−0.9, 0)	(−1.5, 0)	(−2.1, 0)
J1806+6949	0.3	(−1.2, 0.3)	(−1.5, 0.3)	(−2.1, 0.6)
J1824+5651	0.2	(−0.4, 0.6)	(−0.4, 0.8)	(−0.6, 1)
J2005+7752	0.3	(−0.9, 0)	(−1.2, 0)	(−1.5, 0)
J2202+4216	0.2	(0, 1.2)	(0.2, 1.6)	(0.4, 2.4)

measure distribution, the sources considered had to be corrected for this Galactic Faraday rotation. The corrections used come from four different studies; Pushkarev (2001), Rudnick & Jones (1983), Rusk (1988) and Wrobel (1993). The observations of Pushkarev were carried out at six frequencies (1664.9, 1635.1, 1515.9, 1467.7, 1417.5, and 1365.1 MHz), using the VLA. Rudnick & Jones (1983) used VLA observations at 1.5 GHz and 1.6 GHz to derive their Faraday rotations. The observations used by Rusk (1988) were obtained using the VLA at 4860 MHz and 14940 MHz. The RM observations of Wrobel (1993) were obtained using the VLA at six frequencies between 1385.1 MHz and 1664.9 MHz.

The corrections used for each source are referred to in Table 3.5. The Galactic rotation measure was simply subtracted from the calculated rotation measure to create a corrected rotation measure. The rotation measure maps presented have been corrected for the Galactic Rotation measure. However, the intrinsic polarisation angles (χ_0) were obtained using the uncorrected RM maps as any change in polarisation angle from the Galactic contribution also needs to be removed. Throughout the results sections, contours represent Stokes I . The contours in the Stokes I maps increase by either a factor of $\sqrt{2}$ (I maps on their own) or a factor of 2 (I maps superposed with other maps). As mentioned in Section 2.2 a

Table 3.5: Galactic rotation measure for my sources. These values were subtracted from the observed rotation measure maps.

Source	Galactic Rotation Measure (rad/m/m)	Paper
J0006-0623	+13 $\pm$ 2	Pushkarev (2001)
J0050-0929	−28 $\pm$ 7	Pushkarev (2001)
J0121+1149	+240 $\pm$ 18	Pushkarev (2001)
J0721+7120	−30 $\pm$ 3	Rusk (1988)
J0738+1742	+9 $\pm$ 12	Rusk (1988)
J0748+2400	+21 $\pm$ 2	Pushkarev (2001)
J0818+4222	+19 $\pm$ 9	Rusk (1988)
J0825+0309	+1 $\pm$ 2	Pushkarev (2001)
J0854+2006	+31 $\pm$ 2	Rudnick & Jones (1983)
J0958+6533	−15 $\pm$ 4	Rusk (1988)
J1751+0939	+94 $\pm$ 6	Pushkarev (2001)
J1800+7828	−61 $\pm$ 2	Pushkarev (2001)
J1806+6949	+14 $\pm$ 4	Wrobel (1993)
J1824+5651	+36 $\pm$ 4	Wrobel (1993)
J2005+7752	−20 $\pm$ 3	Rusk (1988)
J2202+4216	−205 $\pm$ 6	Rudnick & Jones (1983)

restoring beam (CLEAN beam) is used as part of the imaging process. This is usually an ellipse defined in terms of the full width at half-maximum of its semi-major axis (B_{maj}), semi-minor axis (B_{min}), and beam position angle (BPA). Schematically, this is shown in Figure 3.3. In all cases, maps made are presented using both elliptical convolving beams and circular convolving beams with equal areas and are displayed next to each other. The radius r of this circular beam is taken to be $r = \sqrt{B_{\text{maj}}B_{\text{min}}}$. As the shape of this beam can influence any results and conclusions made, if the same features of interest occur with both beams, they are more likely to be genuine. This is particularly useful, as circular beams do not bias resolution in any direction, and do not give a false sense of jet direction when the ellipse is tilted at an angle or is particularly elongated.

All relevant parameters relating to the overlaying intensity maps are summarised in tabular form in Appendix A. Polarisation maps for all of these sources at 15 GHz, 23 GHz, and 43 GHz can be found on the MOJAVE website. Also available on the MOJAVE website are RM and χ_0 maps, made between 8 and 15 GHz as part of a study by Hovatta et al. (2012). The χ_0 maps of Hovatta et al. (2012) will be regularly referred to but the RM maps are not directly comparable to my own, due to the very different scales they probe and their much lower sensitivity to Faraday rotation.

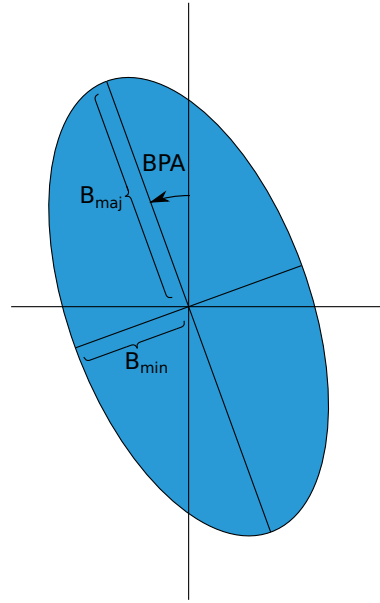


Figure 3.3: Illustration of beam parameters. Usually B_{maj} and B_{min} are described in units of milliarcseconds while BPA is defined in degrees.

A set of four figures is shown for each source studied: (1) Stokes I maps at 5 and 1.45 GHz, together with spectral index maps made between these two frequencies; (2) Stokes I maps at 5 GHz and 1.45 GHz superposed with equal-length EVPA sticks corrected for the Galactic RM only and the Stokes I 1.45 GHz map superposed with EVPA sticks corrected for both Galactic and local RM (the latter giving the distribution of χ_0); (3) Stokes I maps at 5 GHz and 1.45 GHz superposed with the corresponding distributions of fractional polarisation, together with similar maps at 15 GHz and tapered 15 GHz Stokes I maps from the MOJAVE site, for reference; and (4) the Stokes I map superposed with the RM distribution and the RM error distribution, together with plots of the significance of transverse RM gradients for slices taken across the jet at different distances from the core, when reliable, statistically significant transverse RM gradients have been detected. Following any rotation of the RM map, the zero position on the significance plots corresponds to the leftmost pair of pixels (indicated by the solid black line) with measured RM encountered. These pixels form the start and end rotation measures of the slice. Gaps in significance plots correspond to transverse RM gradients which or not monotonic or to regions where there are no RM values present.

3.2 Results

3.2.1 J0006-0623

J0006-0623 has a redshift of $z = 0.3467$ (Jones et al. 2005). Although little structure can be discerned from the 1.45 GHz intensity map, it can be seen from the 5 GHz map in Figure 3.4 as well as from smaller-scale observations such as the 15 GHz MOJAVE observations, that the jet is inclined at an angle of roughly $\theta = -80^\circ$ to the vertical. This was the basis for the jet direction used to take slices in the rotation measure maps of Figure 3.7. In addition, the core-jet gradient in the spectral-index maps in Figure 3.4 is consistent with this jet direction.

The polarisation angles corrected for RM_{Gal} and the χ_0 maps are shown in Figure 3.5. Previous smaller-scale studies, such as the 15 GHz MOJAVE observations, Hovatta et al. (2012)'s χ_0 map and $\lambda = 6$ cm observations by Gabuzda et al. (2000) show that the polarisation exhibits a double structure. EVPAs are perpendicular to the jet direction in the core and inner jet, becoming parallel in the outer jet, Gabuzda et al. (2000) notes the jet component also has perpendicular EVPAs. This change may be down to source variability or not detecting the outer component.

A hint of this double structure is visible in the 5 GHz maps (which is not greatly affected by RM) with the core EVPAs remaining perpendicular to the jet direction and possible alignment with the jet is seen towards the western side of the maps. This is consistent with the 15 GHz MOJAVE maps and indicates an orthogonal magnetic field. The 1.45 GHz χ_0 map (bottom panel) shows perpendicular EVPAs across the entire source. The fractional polarisation (Figure 3.6) increases towards the edges of the jet. This could be due to a helical field or interaction with the ambient medium.

Previous searches in Mahmud & Gabuzda (2008) show a tentative transverse RM gradient in the core region of the source. The rotation measure maps shown in Figure 3.7 show two main regions with possible transverse gradients. The first region extends from a relative right ascension of roughly 10 to 0 mas, is statistically significant (greater than 3σ), and is consistent in both the circular and elliptical beam images. The other possible region of rotation measure gradient is located towards the western end of the RM distribution. In both instances, these possible transverse RM gradients are in the same direction as the gradient found by Mahmud & Gabuzda (2008).

At the same time, these nominally significant gradients are not clearly visible by eye, and this result is limited by the resolution afforded by the relatively large and

elliptical 1.45 GHz restoring beam. To help verify the possible transverse RM, a smaller beam size can be used. This has been done before in previous RM gradient analyses. For example in Gabuzda et al. (2017), as well as using a large 4.6 GHz beam in RM maps of BL-Lac, a 7.9 GHz beam (about a factor of 0.6 smaller) was used for verification. This technique is justified by Coughlan & Gabuzda (2016), who used Monte Carlo simulations to show that both Maximum-Entropy and CLEAN deconvolutions gave trustworthy results for intensity, polarisation, and RM images with restoring beams as small as 50% their intrinsic size. For my work, the 2.2 GHz beam (S Band), which is about two-thirds of the 1.45 GHz beam, would be applicable, the results of which are shown in Figure 3.8. When convolved with the 2.2 GHz circular beam, the transverse rotation measure gradient in the region between a relative right ascension of 10 to 0 mas drops below a significance of 2σ , throwing the veracity of any RM gradient in this region into doubt. However, the transverse RM gradient in the second region appears more obvious to the eye, the significance of which exceeds 8σ . In addition, the structure of the two significance plots has become more similar. Overall, convolution with the 2.2 GHz beam strengthens the argument for a genuine transverse RM gradient in the jet of this source.

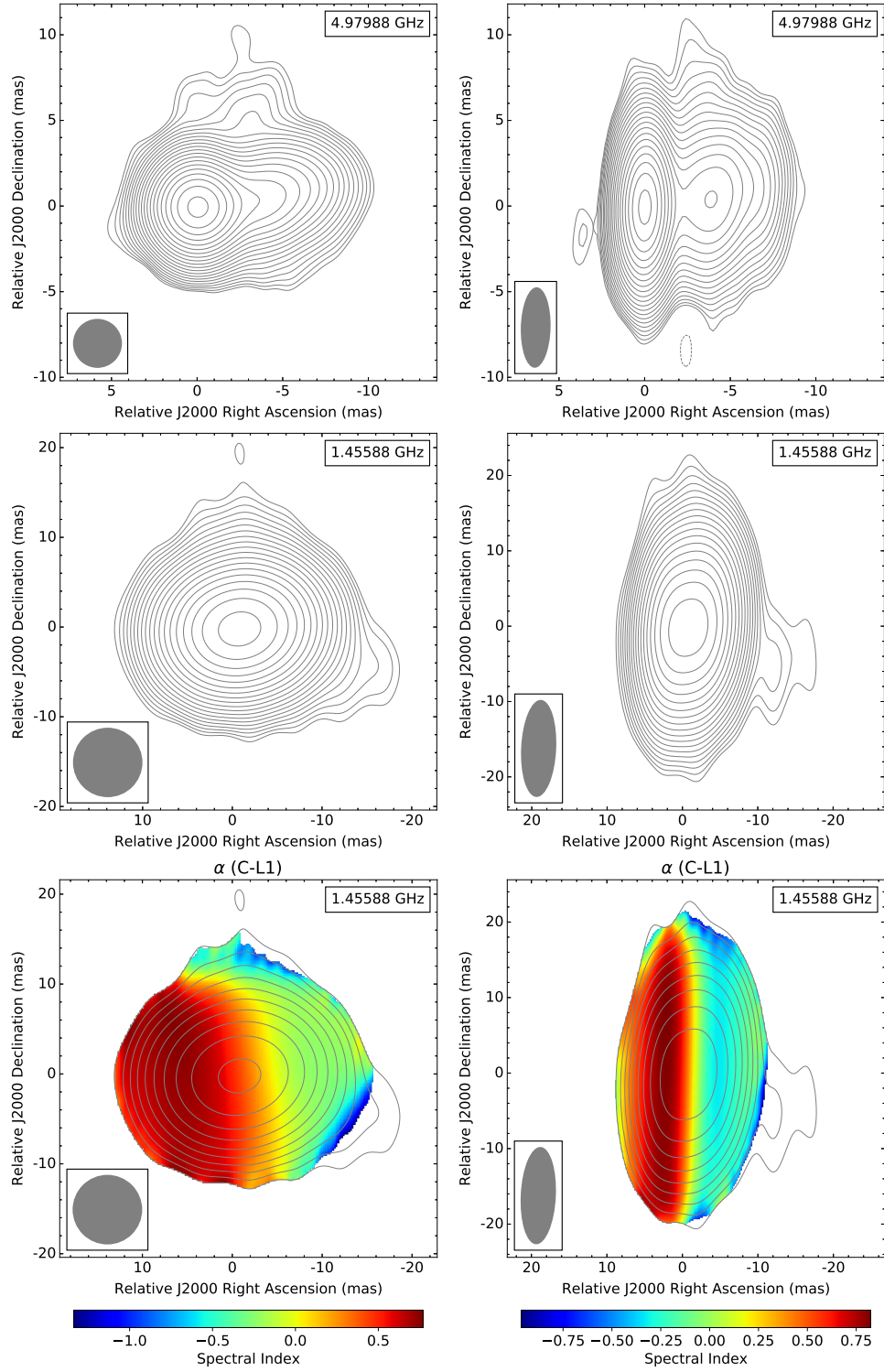


Figure 3.4: The top two panels depict the 5 GHz intensity maps for J0006-0623 convolved with the circular (left) and elliptical (right) 5 GHz beam. The middle two panels show the same for the 1.45 GHz intensity maps convolved with the 1.45 GHz beam. The bottom two panels show the C-L1 spectral index maps for J0006-0623 convolved with the 1.45 GHz beams. Intensity contours for the panels in the first two rows increase in factors of $\sqrt{2}$ and in the bottom row by factors of 2.

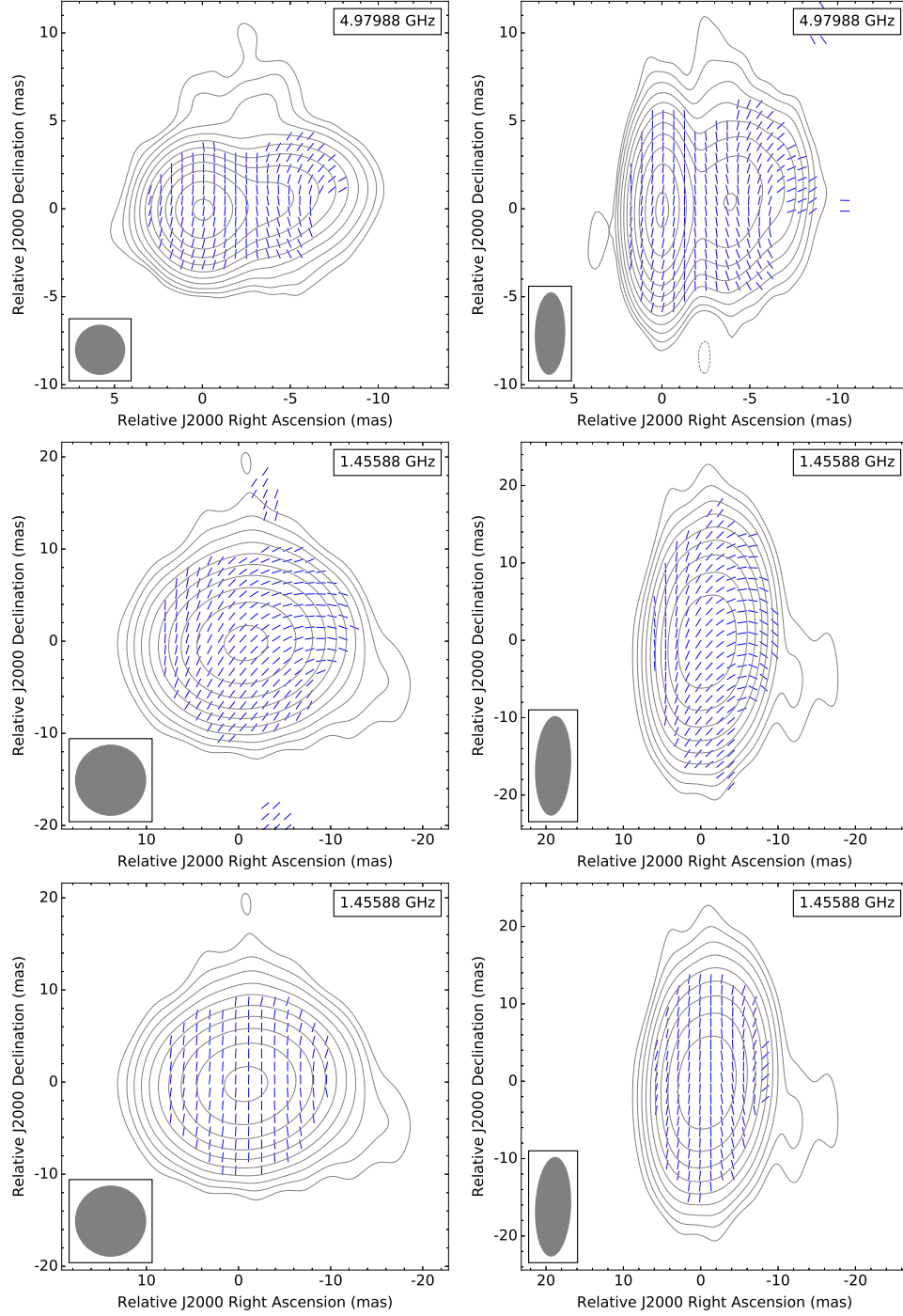


Figure 3.5: The top two panels depict the 5 GHz polarisation angle maps for J0006-0623 corrected for only the Galactic RM convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz polarisation angle maps corrected for only the Galactic RM convolved with the 1.45 GHz beam. The bottom two panels show the 1.45 GHz χ_0 maps convolved with the 1.45 GHz beams. The polarisation intensity cutoffs for the top four panels are 3 mJy/beam (5 GHz circular beam), 1.5 mJy/beam (5 GHz elliptical beam), 1.25 mJy/beam (1.45 GHz circular beam) and 1.4 mJy/beam (1.45 GHz elliptical beam).

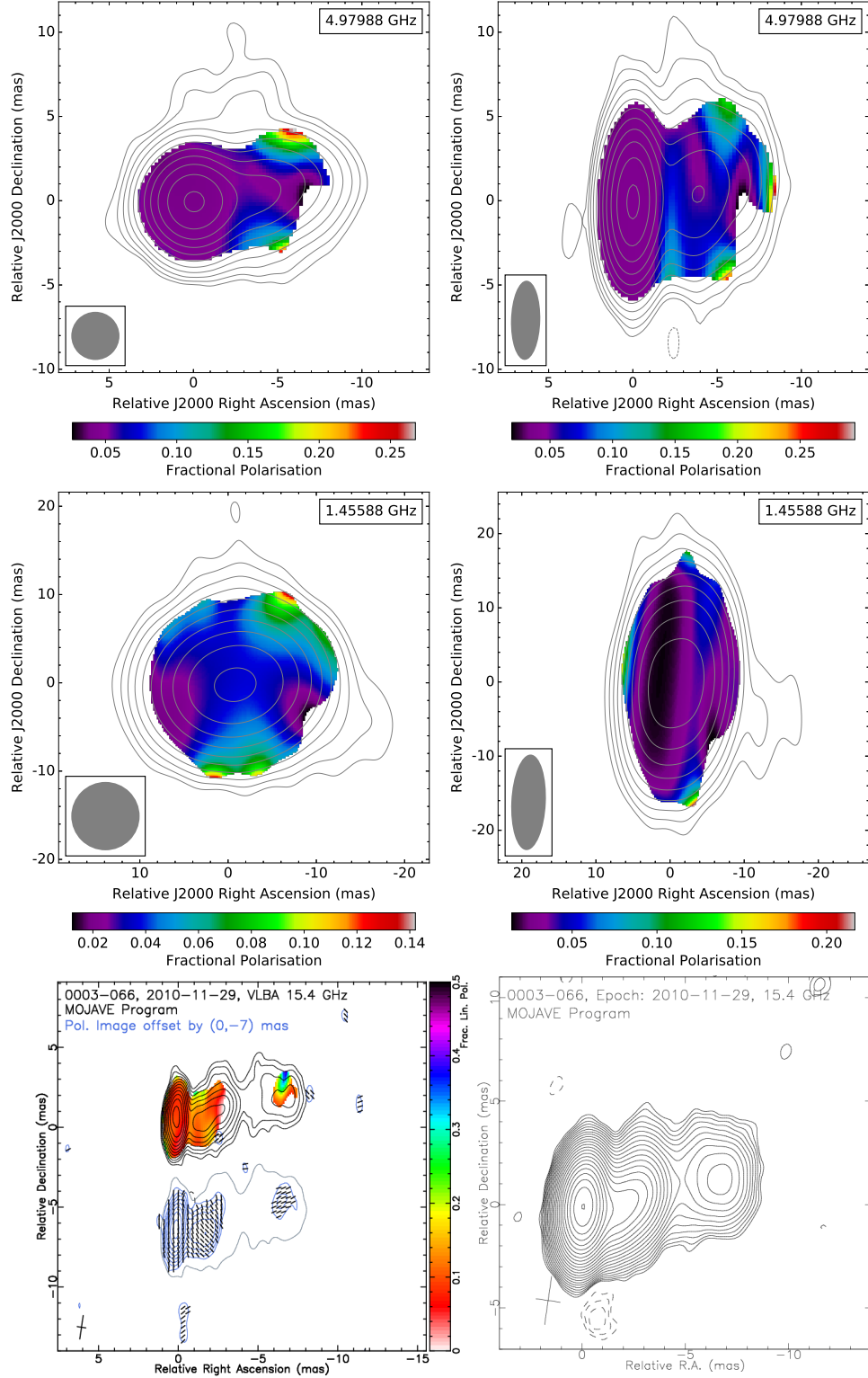


Figure 3.6: The top two panels show the 5 GHz fractional polarisation maps for J0006-0623 convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz fractional polarisation maps convolved with the 1.45 GHz beam. Polarisation intensity cutoffs are the same as in Figure 3.5. The bottom two panels show the 15 GHz MOJAVE polarisation and fractional polarisation (left) and tapered intensity (right) maps from 29/11/2010.

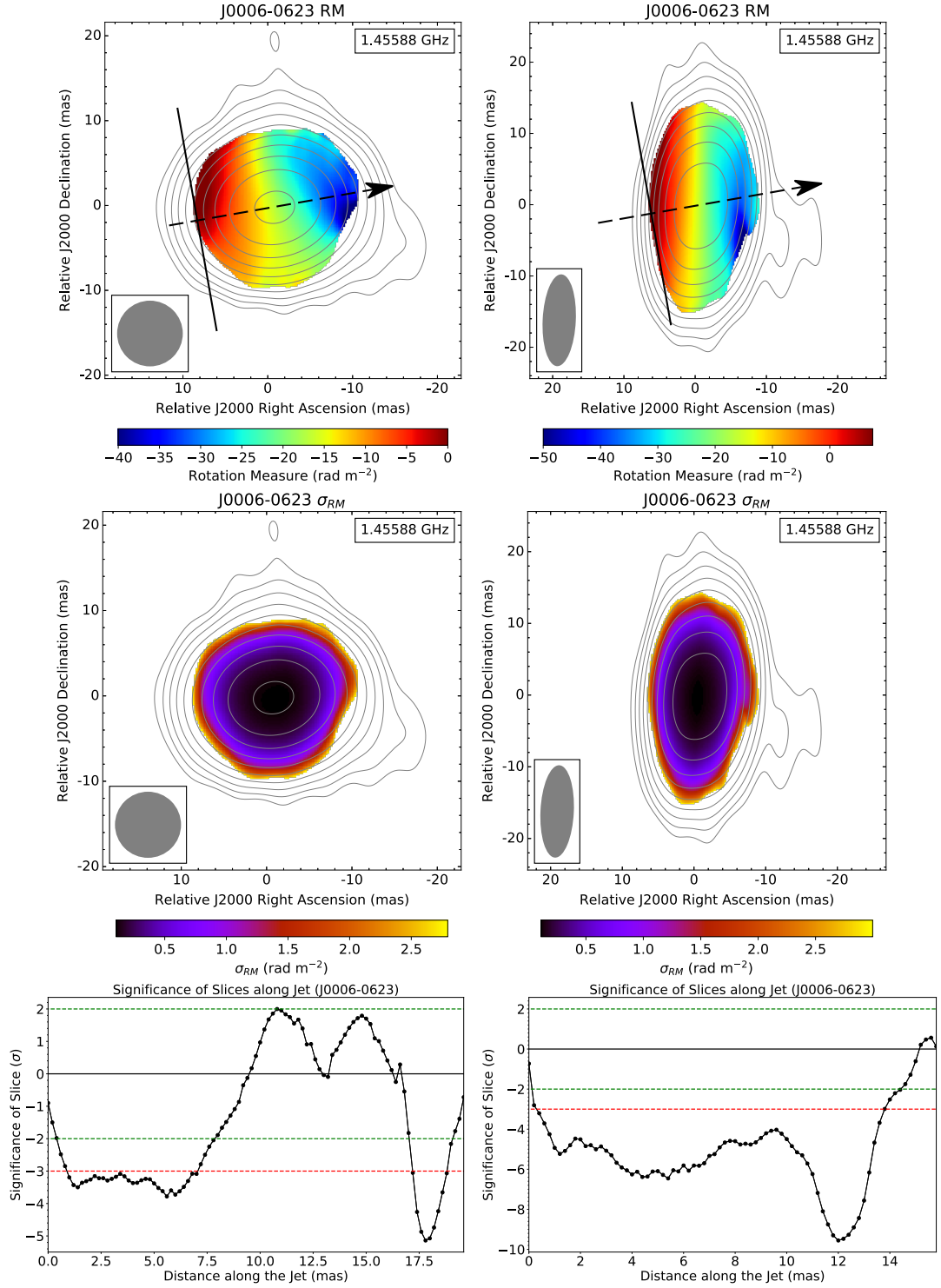


Figure 3.7: The top two panels depict the rotation measure maps for J0006-0623 convolved with the circular (left) and elliptical (right) 1.45 GHz restoring beams. The middle two panels show the corresponding error maps. The bottom two panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrow shown in the top two panels.

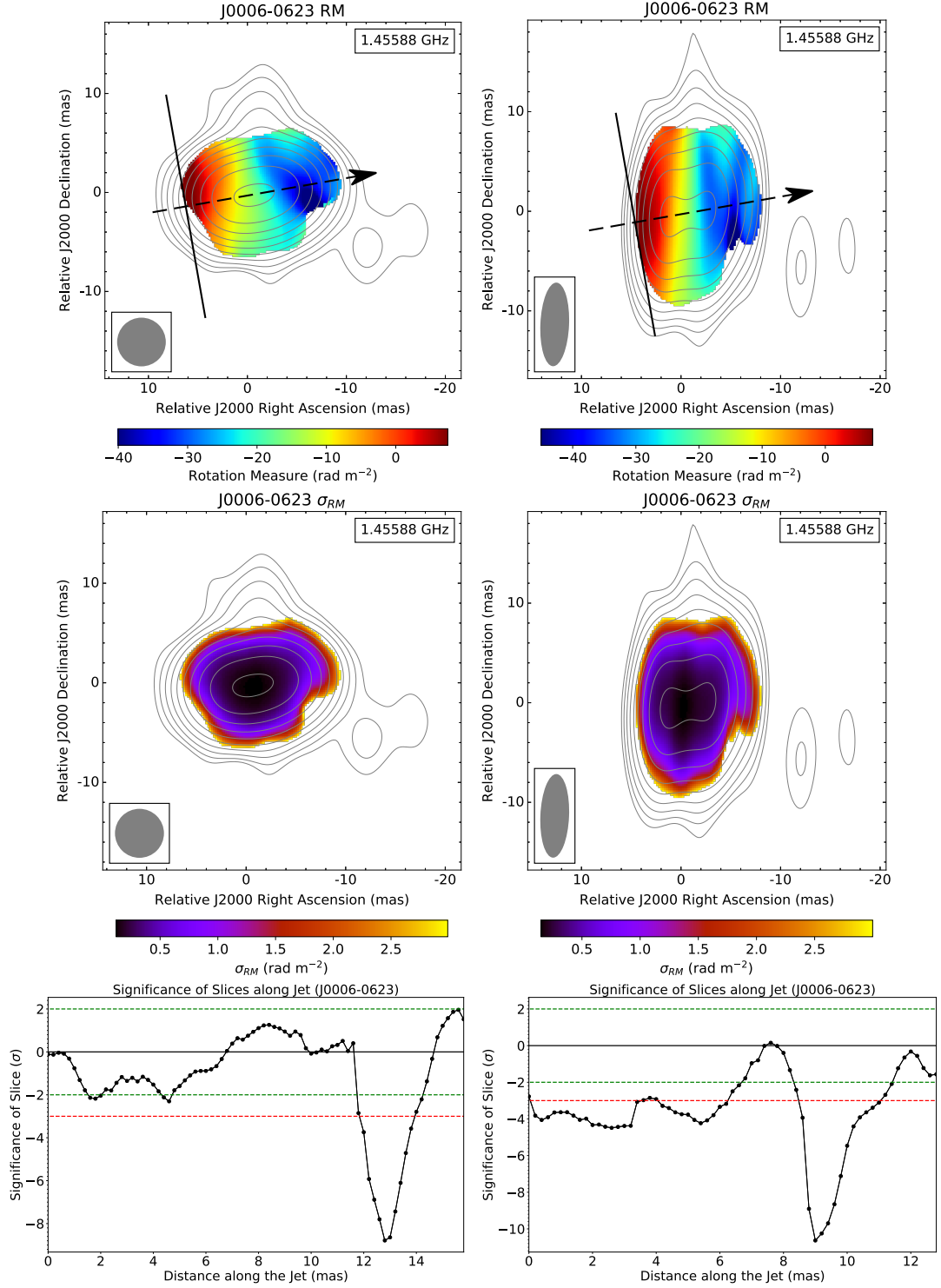


Figure 3.8: The top two panels depict the rotation measure maps for J0006-0623 convolved with the circular (left) and elliptical (right) 2.2 GHz restoring beams. The middle two panels show the corresponding error maps. The bottom two panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrow shown in the top two panels.

3.2.2 J0050-0929

J0050-0929 has a redshift of $z = 0.635$ (Landoni et al. 2012). The 5 GHz and 1.45 GHz intensity maps in Figure 3.9 show a strong jet at a position angle $\theta = 10^\circ$. However, on smaller scales, such as the MOJAVE 15 GHz observations as well the 23 GHz and 43 GHz observations from the RRIFD Database, it can be seen that the core inner jet direction is north-west with a position angle closer to $\theta = -20^\circ$. The spectral index map is as expected for a partially optically thick core, with α decreasing with distance from the core. The core-jet gradient in the spectral index map also suggests a position angle of $\theta \approx -20^\circ$. This was the basis for the choice of jet direction shown in Figure 3.12.

The 15 GHz MOJAVE observations show polarisation limited to the core, with EVPAs varying over time and not showing any clear relation to the jet direction. This echoes what is shown in Figure 3.10. At a relative declination of 10 to 16 mas, the χ_0 map shows a hint of the polarisation angles being aligned with the jet. This could be evidence of an orthogonal magnetic field but not enough data is present to draw any solid conclusions about the polarisation angle structure. Furthermore, the RM_{Gal} corrected EVPAs do not seem to be entirely consistent with the χ_0 maps, likely due to the high magnitude calculated RM, meaning that correcting only for Galactic RM ($\text{RM}_{\text{Gal}} = -28 \text{ rad m}^{-2}$) is insufficient to reproduce the intrinsic polarisation angle structure. As expected, the fractional polarisation displayed in Figure 3.11 in the core is low, with $m < 5\%$ at both 5 GHz and 1.4 GHz observations but no discernible structure is seen in the jet, although there is tentative evidence for an increase in fractional polarisation at the jet edges.

The rotation measure maps in Figure 3.12 show a very clear transverse gradient across the core region with 9σ gradients in both the maps convolved with the circular and elliptical beams, implying a toroidal magnetic field component. The direction of this gradient is transverse to the position angle of the jet in the core region, $\text{PA} \approx -20^\circ$. The transverse RM gradient is clearly visible by eye and extends across the entire region of detected rotation measures.

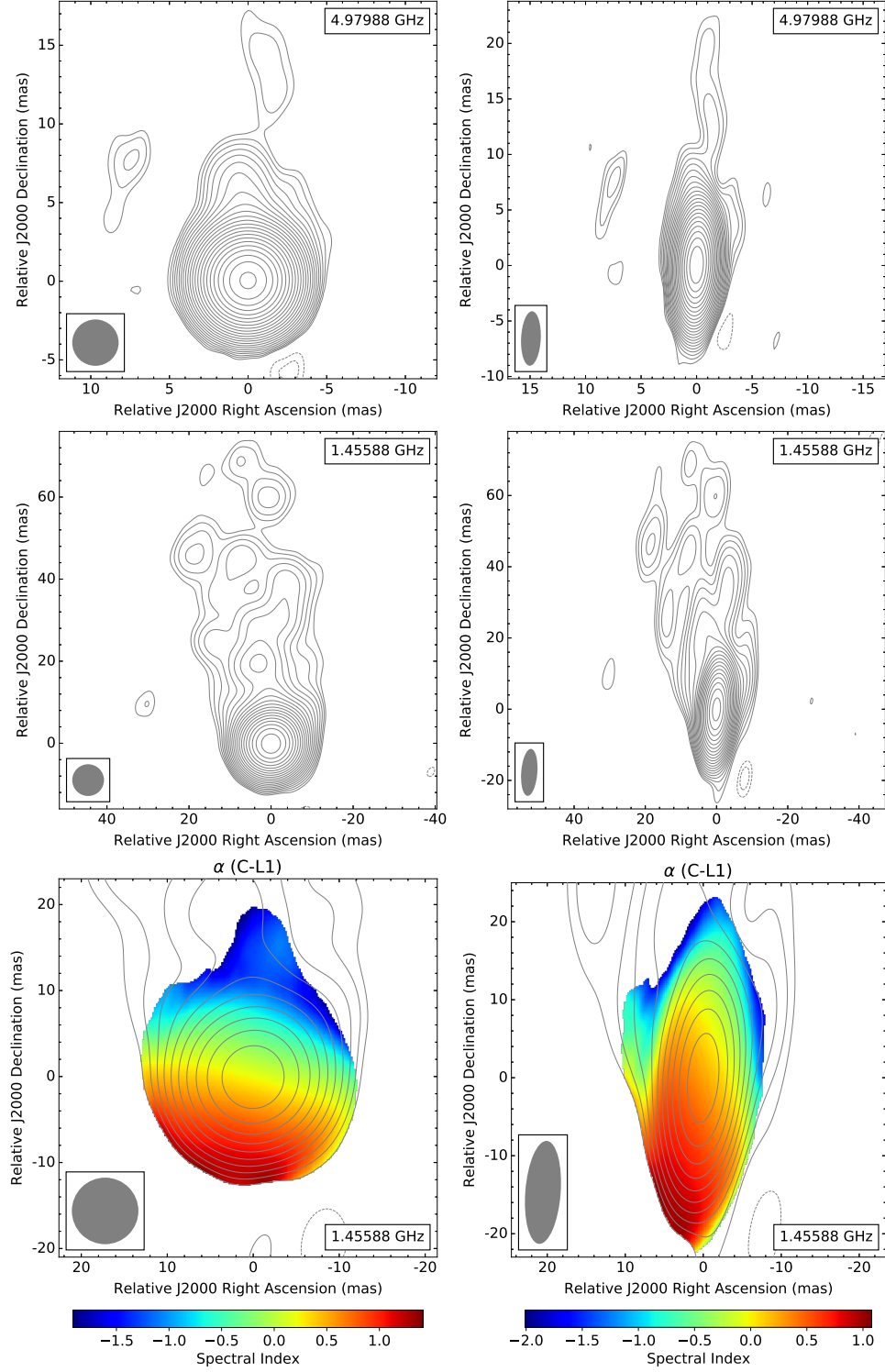


Figure 3.9: The top two panels depict the 5 GHz intensity maps for J0050-0929 convolved with the circular (left) and elliptical (right) 5 GHz beam. The middle two panels show the same for the 1.45 GHz intensity maps convolved with the 1.45 GHz beam. The bottom two panels show the C-L1 spectral index maps for J0050-0929 convolved with the 1.45 GHz beams. Intensity contours for the panels in the first two rows increase in factors of $\sqrt{2}$ and in the bottom row by factors of 2.

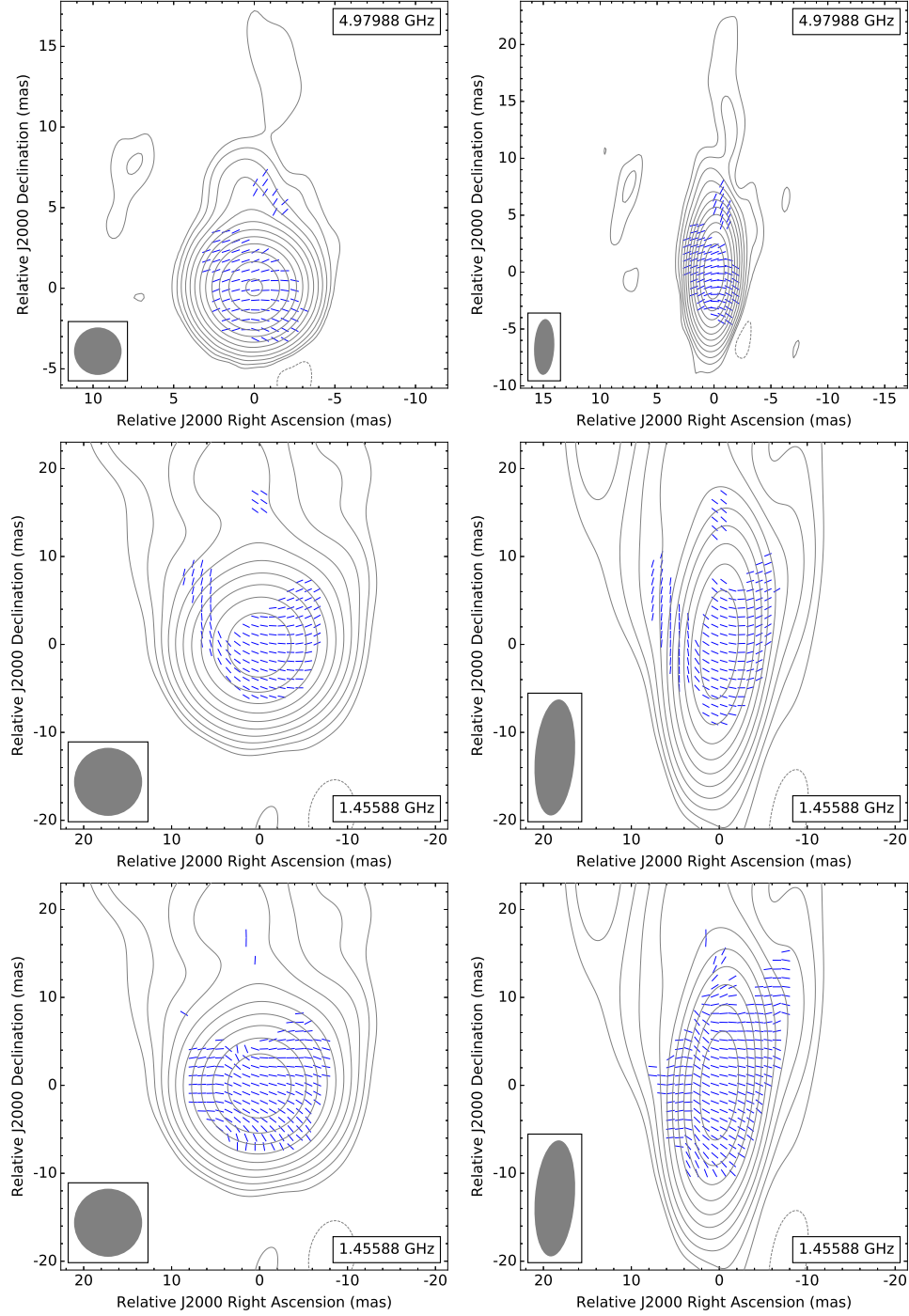


Figure 3.10: The top two panels depict the 5 GHz polarisation angle maps for J0050-0929 corrected for only the Galactic RM convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz polarisation angle maps corrected for only the Galactic RM convolved with the 1.45 GHz beam. The bottom two panels show the 1.45 GHz χ_0 maps convolved with the 1.45 GHz beams. The polarisation intensity cutoffs for the top four panels are 0.35 mJy/beam (5 GHz circular beam), 0.375 mJy/beam (5 GHz elliptical beam), 0.8 mJy/beam (1.45 GHz circular beam) and 0.9 mJy/beam (1.45 GHz elliptical beam).

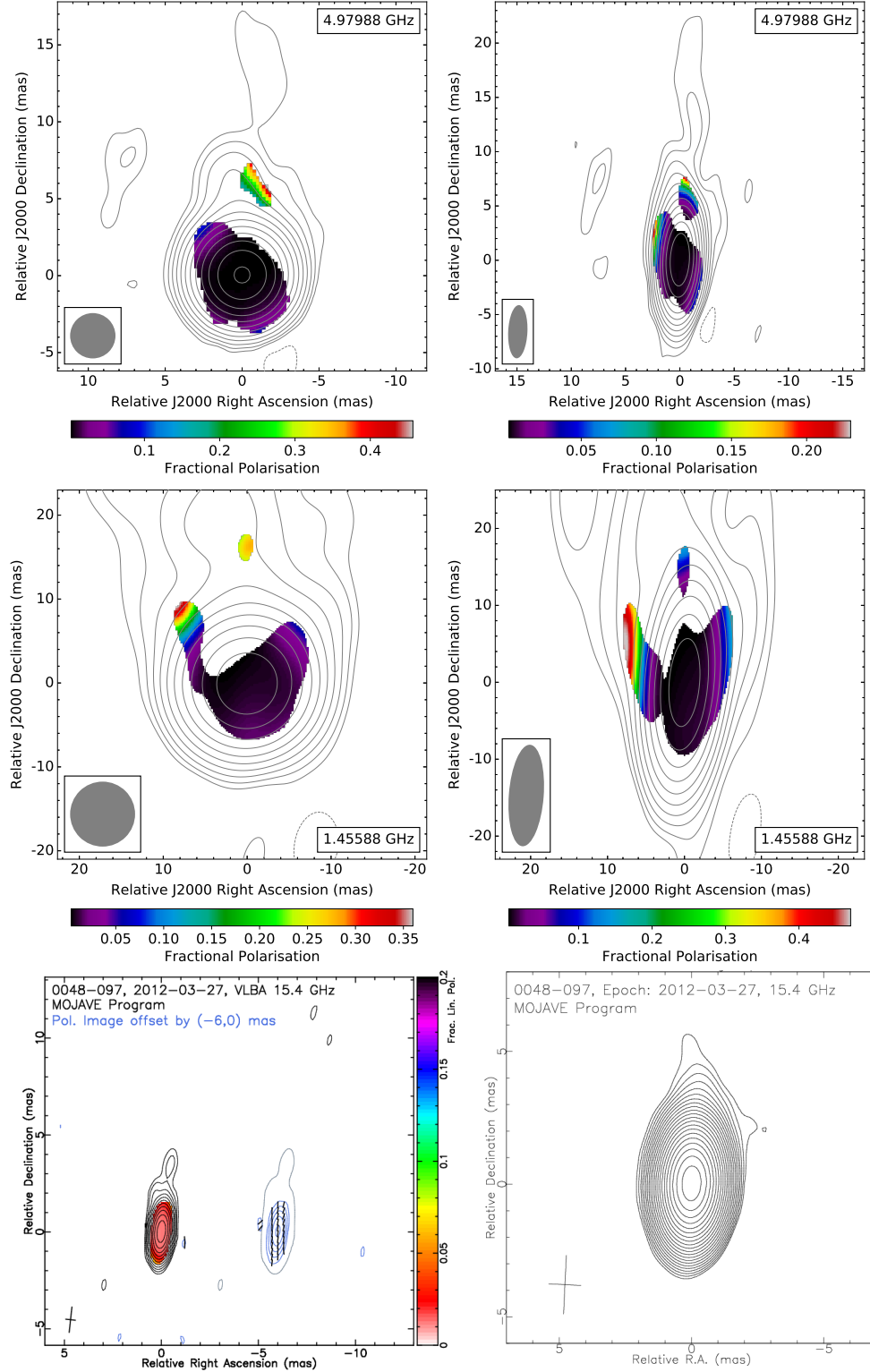


Figure 3.11: The top two panels show the 5 GHz fractional polarisation maps for J0050-0929 convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz fractional polarisation maps convolved with the 1.45 GHz beam. Polarisation intensity cutoffs are the same as in Figure 3.10. The bottom two panels show the 15 GHz MOJAVE polarisation and fractional polarisation (left) and tapered intensity (right) maps from 27/03/2012.

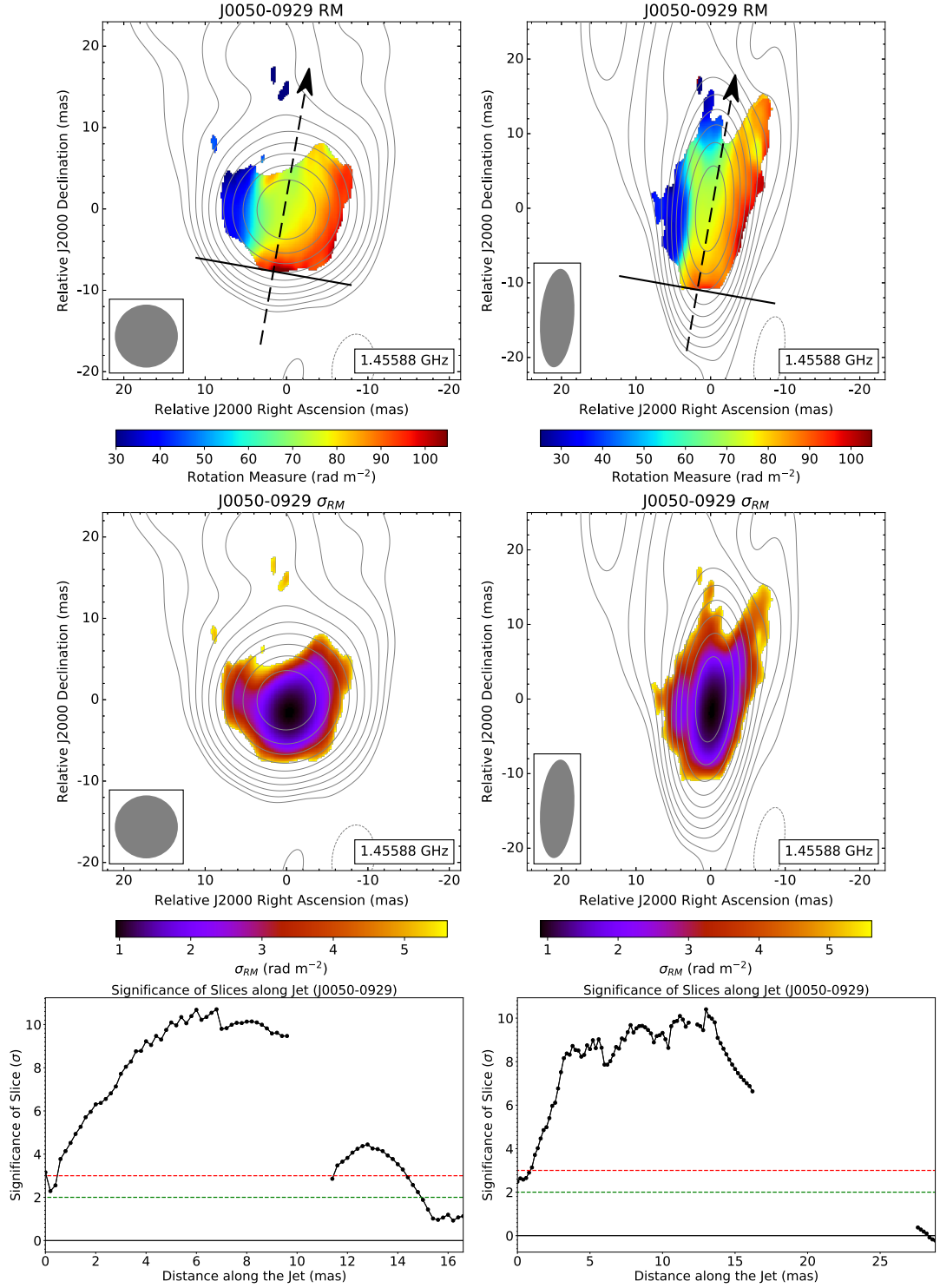


Figure 3.12: The top two panels depict the rotation measure maps for J0050-0929 convolved with the circular (left) and elliptical (right) 1.45 GHz restoring beams. The middle two panels show the corresponding error maps. The bottom two panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrow shown in the top two panels.

3.2.3 J0121+1149

J0121+1149 has a redshift of $z = 0.571$ (Pâris et al. 2017). The 5 GHz and 1.45 GHz intensity maps in Figure 3.13 show a jet that initially emerges at a position angle $\theta = 10^\circ$, then curves to the east. A similar structure is seen in 15 GHz MOJAVE observations as well as the 23 GHz and 43 GHz observations from the RRIFD database. The spectral index is consistent with a partially optically thick core, decreasing with distance down the jet, but suggests an inner jet direction closer to -10° . At the same time, the 15 GHz MOJAVE maps indicate a jet direction close to 0° . An inner jet direction of -10° is assumed in the analysis below, but the results are not significantly affected if the actual inner jet direction is closer to 0° . High-quality VLBA or global VLBI images at 43–86 GHz could help resolve this question, but no such images are currently available.

The polarisation maps in Figure 3.14 show the source only has strong polarisation near the core. Overall, the RM_{Gal} corrected EVPA maps are consistent with the χ_0 maps. In the 1.45 GHz maps, there is a region of interest at a relative declination of 12 to 18 mas, where the polarisation angles are ordered perpendicular to the jet possibly representing the "sheath" in a spine-sheath structure, or the bending of the jet in that region. Notably, the fractional polarisation increases in this region in the 1.45 GHz maps. The polarisation vectors further along the jet in the 1.45 GHz maps are possibly spurious as they are close to the noise level.

The rotation measure maps in Figure 3.16 show a possible transverse rotation measure gradient. This is present in the case of convolution with either the elliptical or circular beam and exceeds a significance of 3σ in both cases. At the same time, this gradient is not clearly visible by eye, and we decided to verify this result, using RM maps convolved with the 2.2 GHz beam. The results are shown in Figure 3.17, which shows that the same transverse RM gradient appears when convolved with the smaller 2.2 GHz beam, and is more clearly visible by eye in the map made with the circular beam. This leads us to consider this transverse RM gradient to be reliable. There is also a hint of a transverse RM gradient in the opposite direction near the start of the statistical significance plot, which would represent an RM gradient reversal if real. However, this covers only about half a beamwidth, and cannot be considered more than tentative. Previously, rotation measure and polarisation angle analysis were done at 18–22 cm by Coughlan et al. (2011) for two epochs in May 2010 and January 2004 although no transverse RM gradients were detected. Further analysis and comparison will be done between the 2004, 2010, and 2017 epoch observations in Chapter 4 of this thesis.

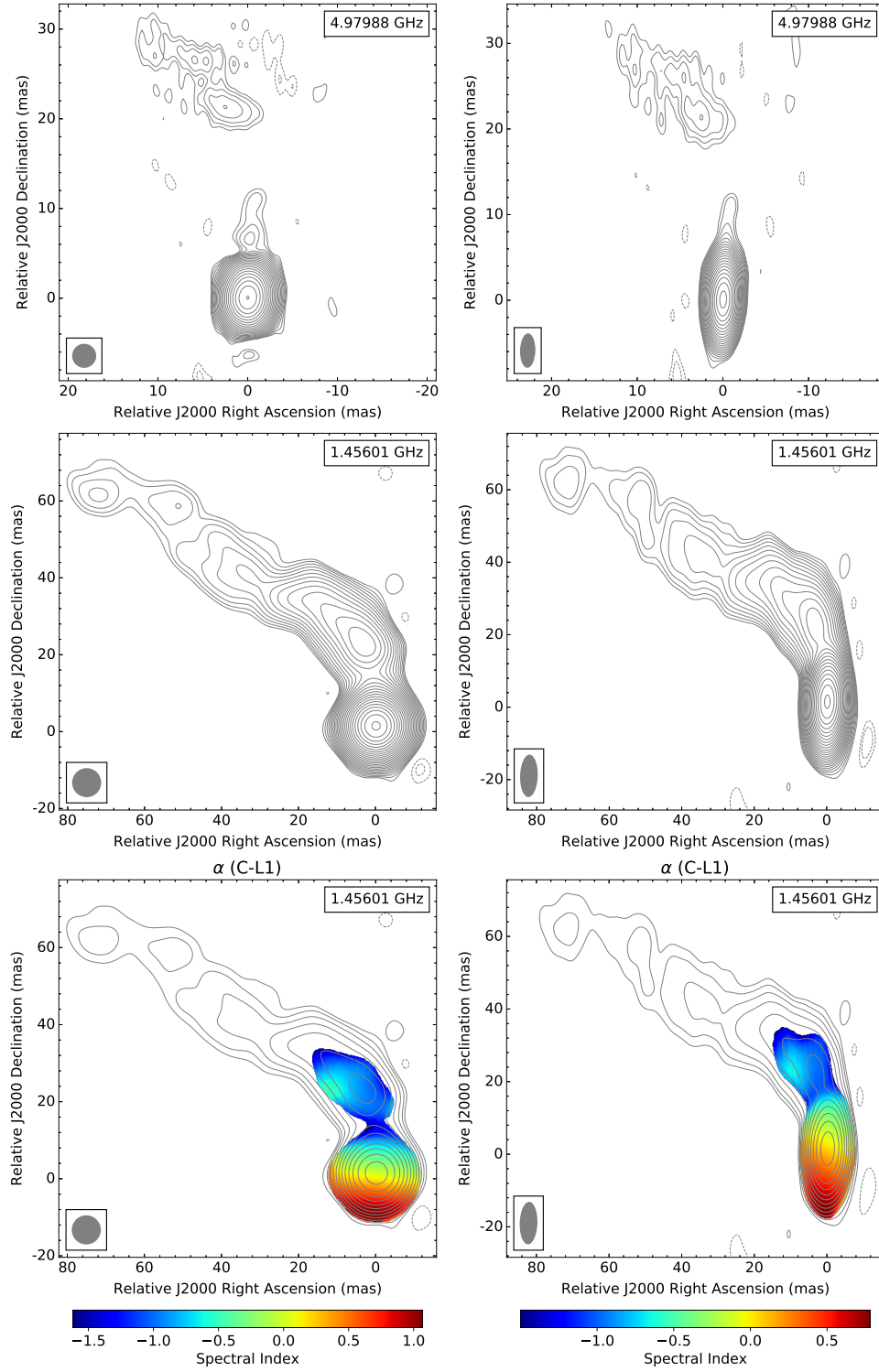


Figure 3.13: The top two panels depict the 5 GHz intensity maps for J0121+1149 convolved with the circular (left) and elliptical (right) 5 GHz beam. The middle two panels show the same for the 1.45 GHz intensity maps convolved with the 1.45 GHz beam. The bottom two panels show the C-L1 spectral index maps for J0121+1149 convolved with the 1.45 GHz beams. Intensity contours for the panels in the first two rows increase in factors of $\sqrt{2}$ and in the bottom row by factors of 2.

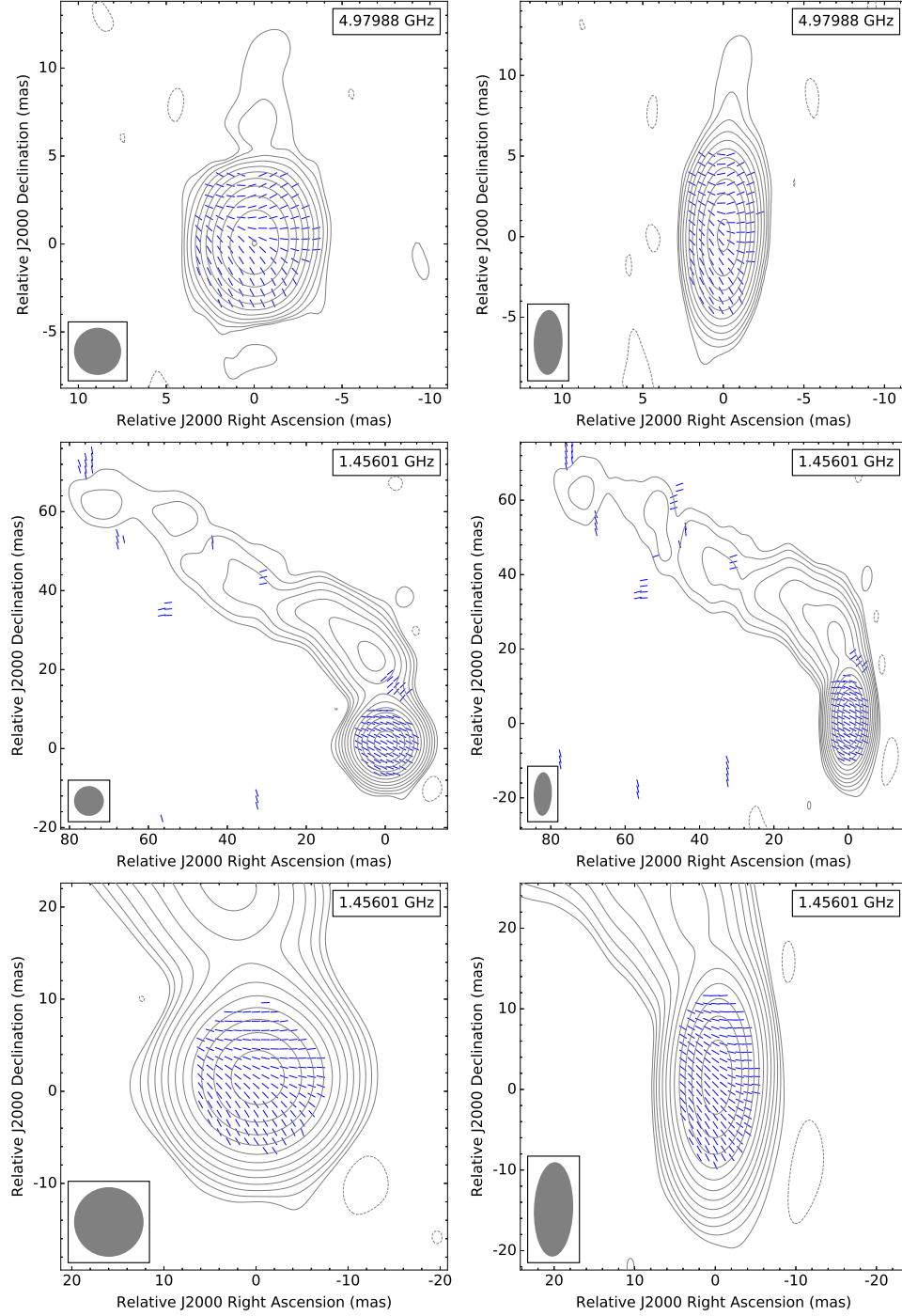


Figure 3.14: The top two panels depict the 5 GHz polarisation angle maps for J0121+1149 corrected for only the Galactic RM convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz polarisation angle maps corrected for only the Galactic RM convolved with the 1.45 GHz beam. The bottom two panels show the 1.45 GHz χ_0 maps convolved with the 1.45 GHz beams. The polarisation intensity cutoffs for the top four panels are 1 mJy/beam (5 GHz circular beam), 0.9 mJy/beam (5 GHz elliptical beam), 2.5 mJy/beam (1.45 GHz circular beam) and 2.6 mJy/beam (1.45 GHz elliptical beam).

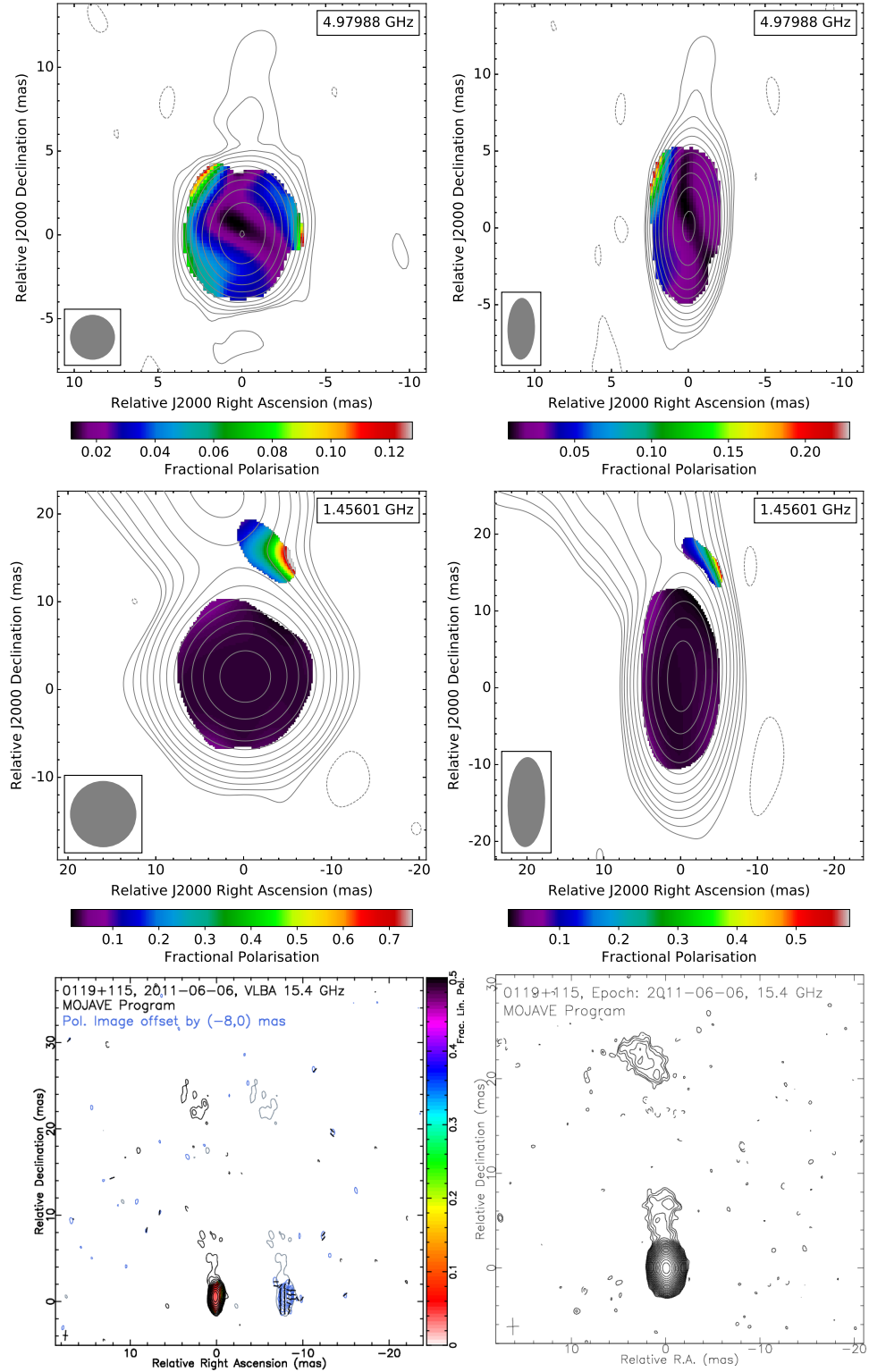


Figure 3.15: The top two panels show the 5 GHz fractional polarisation maps for J0121+1149 convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz fractional polarisation maps convolved with the 1.45 GHz beam. Polarisation intensity cutoffs are the same as in Figure 3.14. The bottom two panels show the 15 GHz MOJAVE polarisation and fractional polarisation (left) and tapered intensity (right) maps from 06/06/2011.

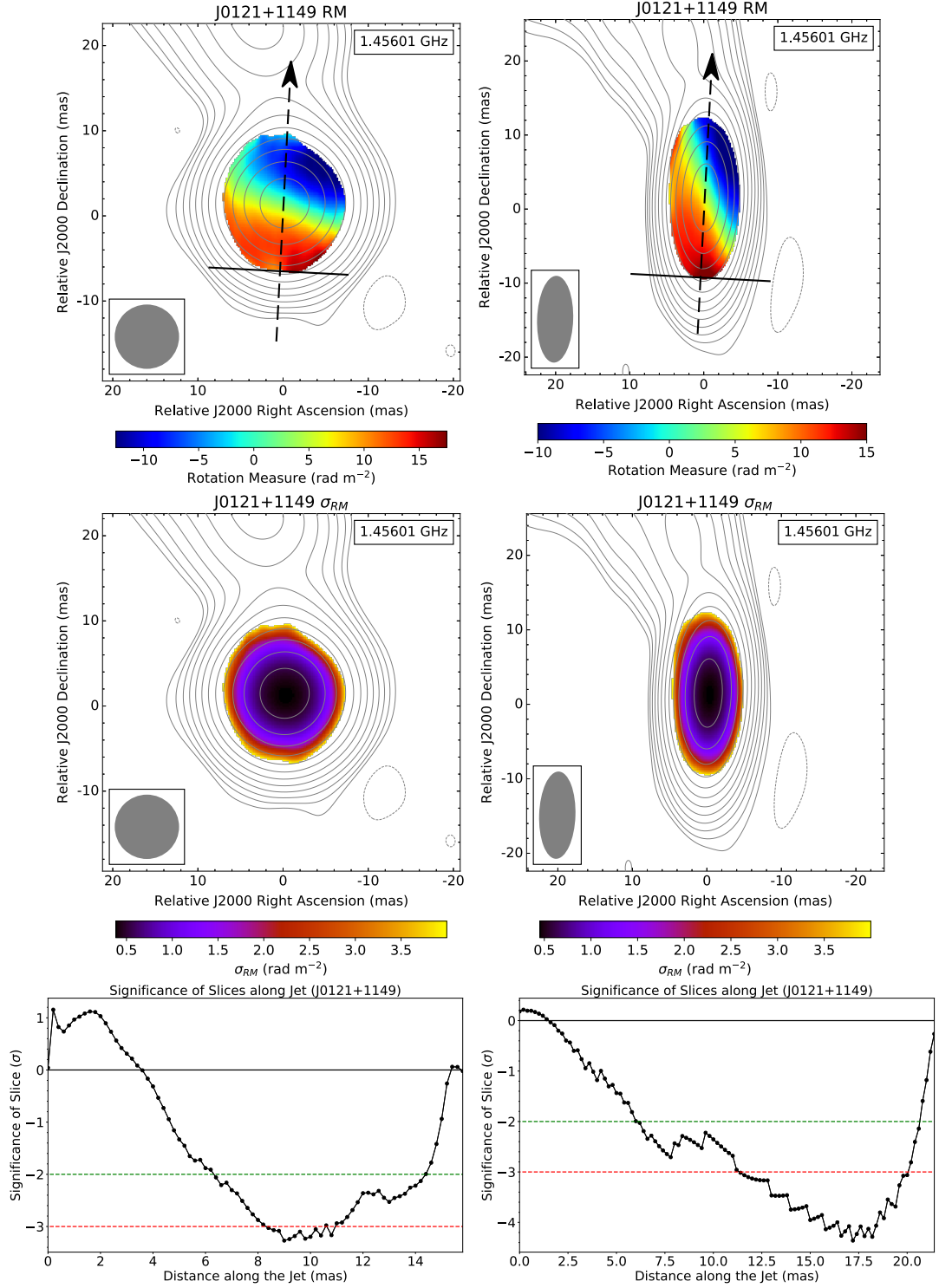


Figure 3.16: The top two panels depict the rotation measure maps for J0121+1149 convolved with the circular (left) and elliptical (right) 1.45 GHz restoring beams. The middle two panels show the corresponding error maps. The bottom two panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrow shown in the top two panels.

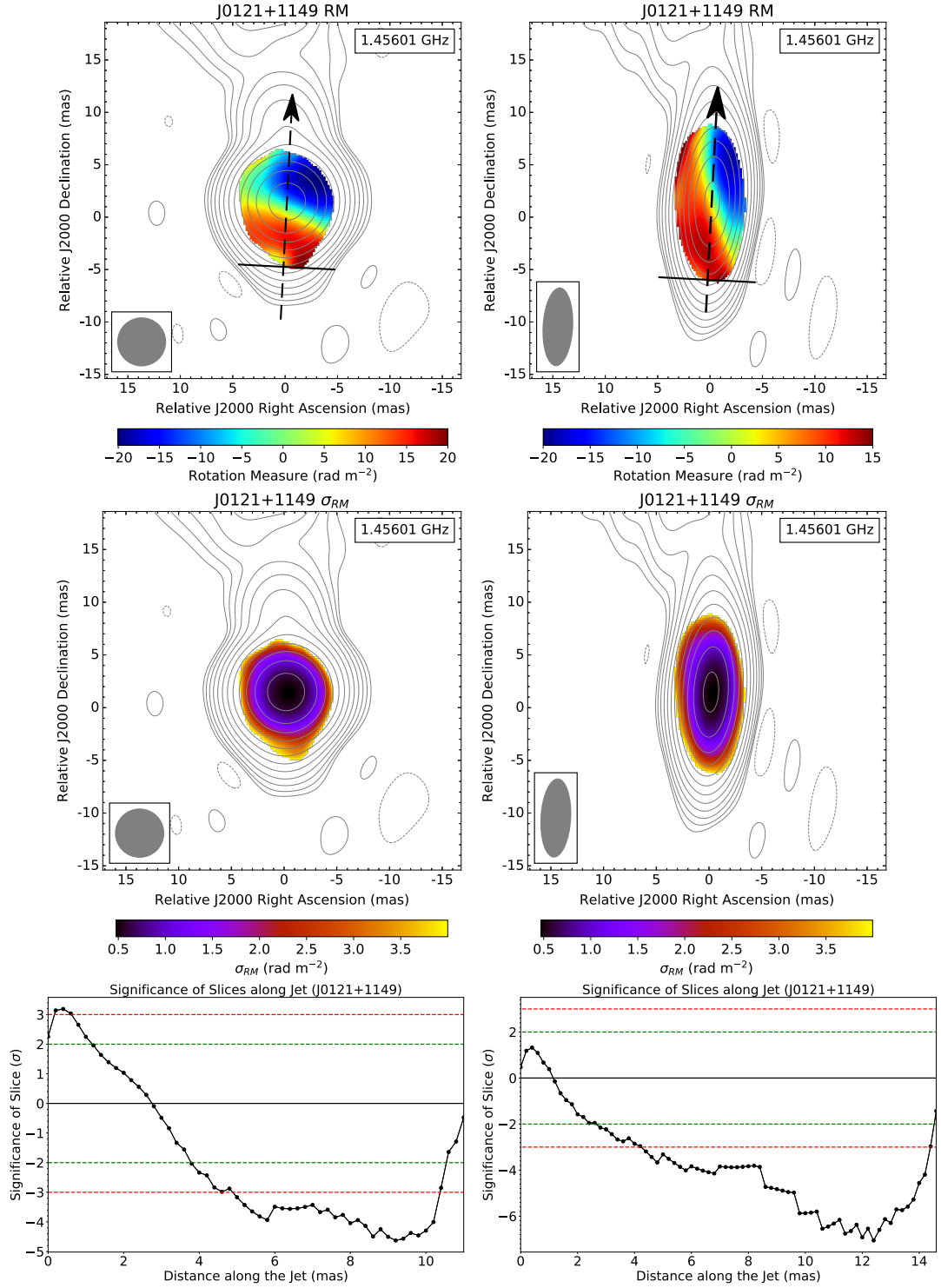


Figure 3.17: The top two panels depict the rotation measure maps for J0121+1149 convolved with the circular (left) and elliptical (right) 2.2 GHz restoring beams. The middle two panels show the corresponding error maps. The bottom two panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrow shown in the top two panels.

3.2.4 J0721+7120

J0721+7120 has redshift of $z = 0.127$ (Stadnik & Romani 2014). Analysis by Gabuzda et al. (1998) conducted over two epochs at 6 cm, 3.6 cm, and 1.3 cm, found the polarisation in the jet of J0721+7120 to be highly variable between the two epochs, which were three years apart. This high variability, which consisted of a shift in polarisation angle by 90° from being aligned with the jet to being perpendicular to the jet, suggested the presence of shocks propagating through the jet. As can be seen in Figure 3.18, the jet initially emerges at a position angle $\theta = 20^\circ$ and extends to a maximum of 120 mas to the north before dissipating. The spectral index maps are consistent with a partially optically thick core, with spectral index decreasing with distance along the jet. The core-jet gradient in our spectral index map is also consistent with this jet direction.

The RM_{Gal} corrected EVPAs in Figure 3.19 are orthogonal to the jet direction (longitudinal magnetic field) in the core and inner jet but become aligned with the jet direction outside of the core, suggesting an orthogonal magnetic field. An orthogonal field suggests either a helical magnetic field or possibly a series of shocks propagating through the jet. To rule out a shock being the cause, one may examine whether or not the polarisation angles are consistently parallel to the jet along its length. If so, a helical field is more likely to be the cause. The EVPAs observed are uniformly parallel to the jet. However, polarisation was not detected adequately far into the jet to say whether or not it remains uniform along the entire length.

The fractional polarisation maps in Figure 3.20 show the core region is polarised with $m \approx 10\%$ at both 5 GHz and 1.45 GHz. In the jet, this increases to roughly 30% polarisation. There is some evidence that the amount of polarisation increases towards the edge of the jet in the 5 GHz polarisation distribution but this is not evident in the 1.45 GHz maps.

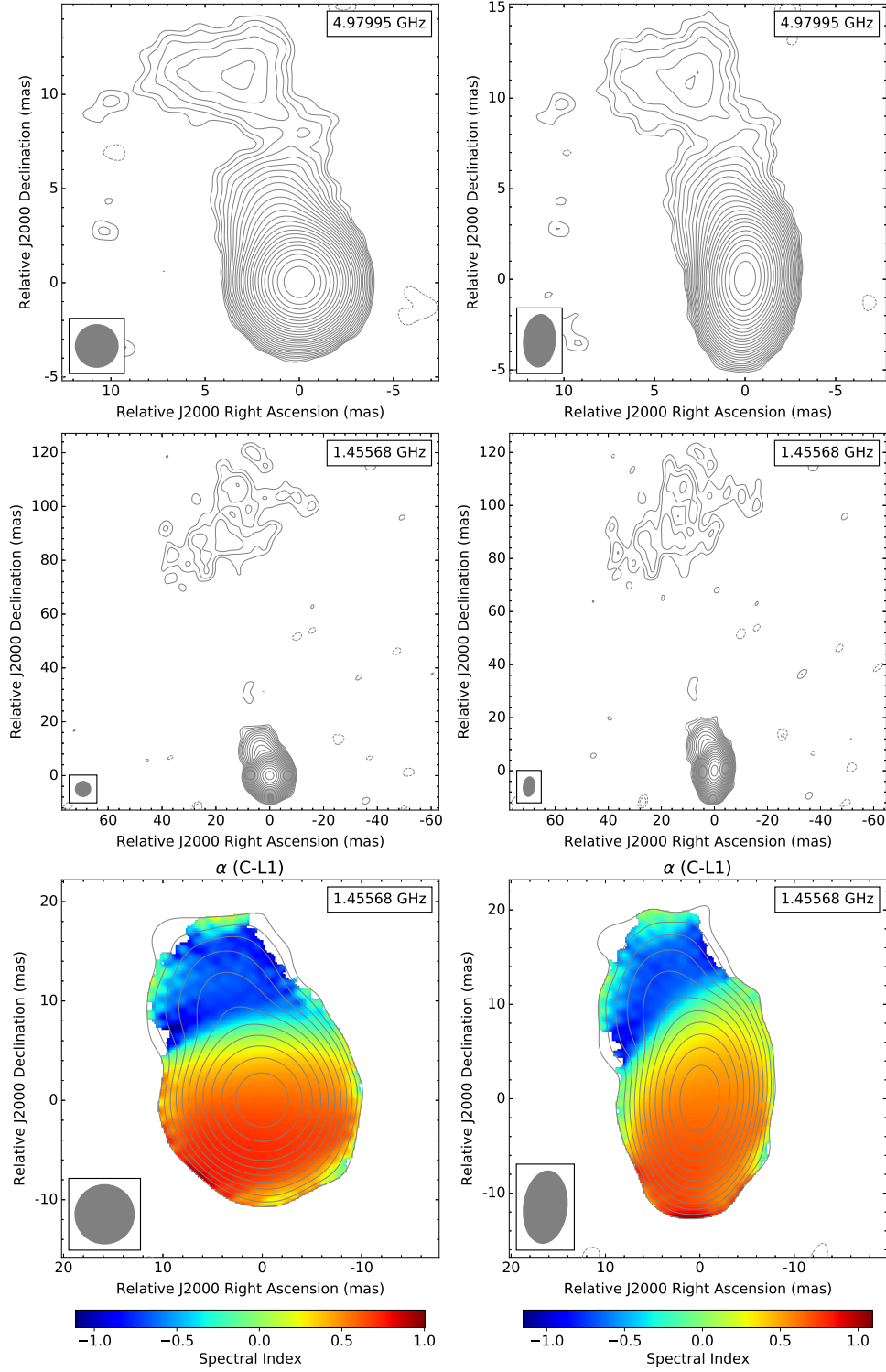


Figure 3.18: The top two panels depict the 5 GHz intensity maps for J0721+7120 convolved with the circular (left) and elliptical (right) 5 GHz beam. The middle two panels show the same for the 1.45 GHz intensity maps convolved with the 1.45 GHz beam. The bottom two panels show the C-L1 spectral index maps for J0721+7120 convolved with the 1.45 GHz beams. Intensity contours for the panels in the first two rows increase in factors of $\sqrt{2}$ and in the bottom row by factors of 2.

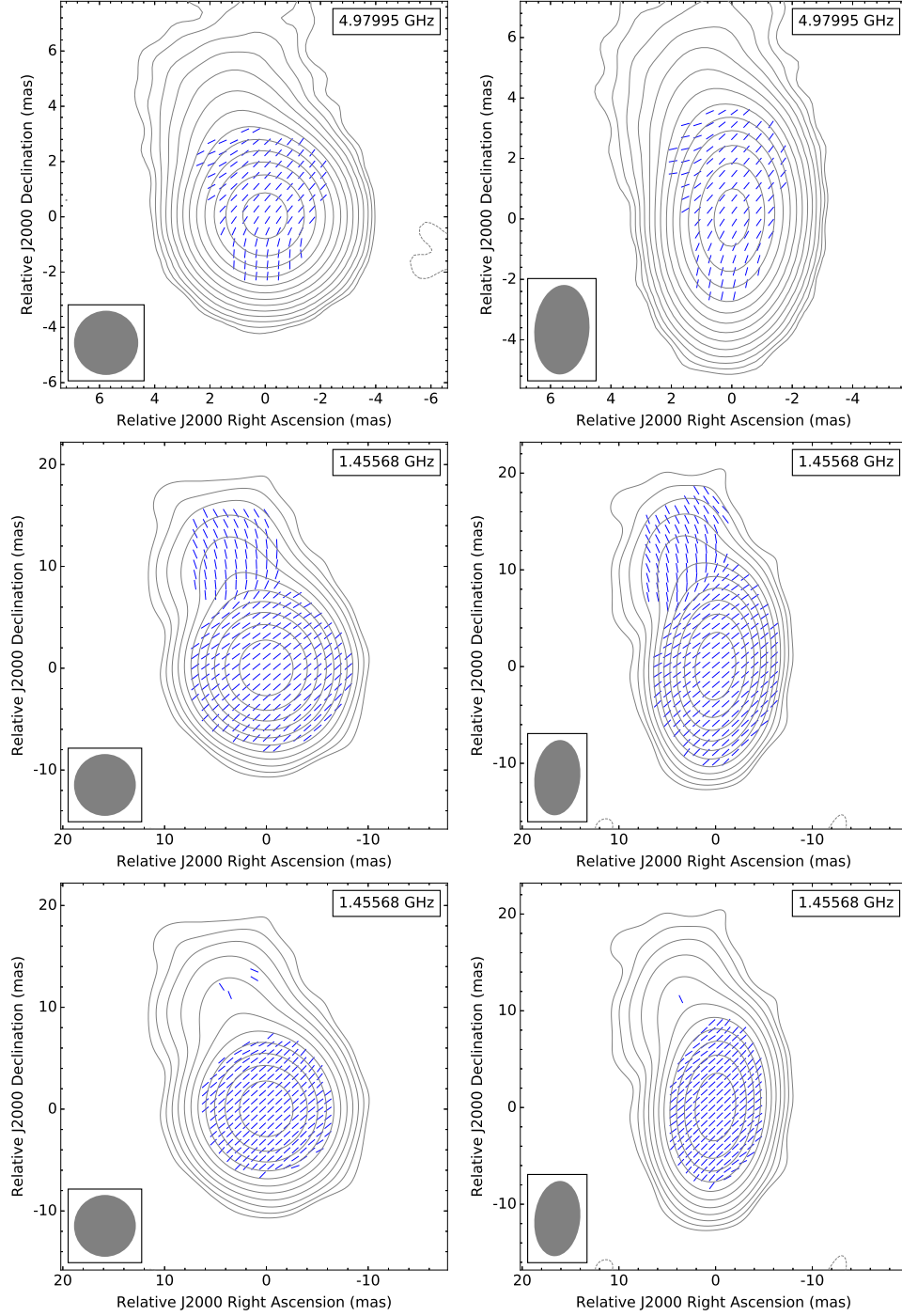


Figure 3.19: The top two panels depict the 5 GHz polarisation angle maps for J0721+7120 corrected for only the Galactic RM convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz polarisation angle maps corrected for only the Galactic RM convolved with the 1.45 GHz beam. The bottom two panels show the 1.45 GHz χ_0 maps convolved with the 1.45 GHz beams. The polarisation intensity cutoffs for the top four panels are 1.1 mJy/beam (5 GHz circular beam), 1.1 mJy/beam (5 GHz elliptical beam), 0.5 mJy/beam (1.45 GHz circular beam) and 0.4 mJy/beam (1.45 GHz elliptical beam).

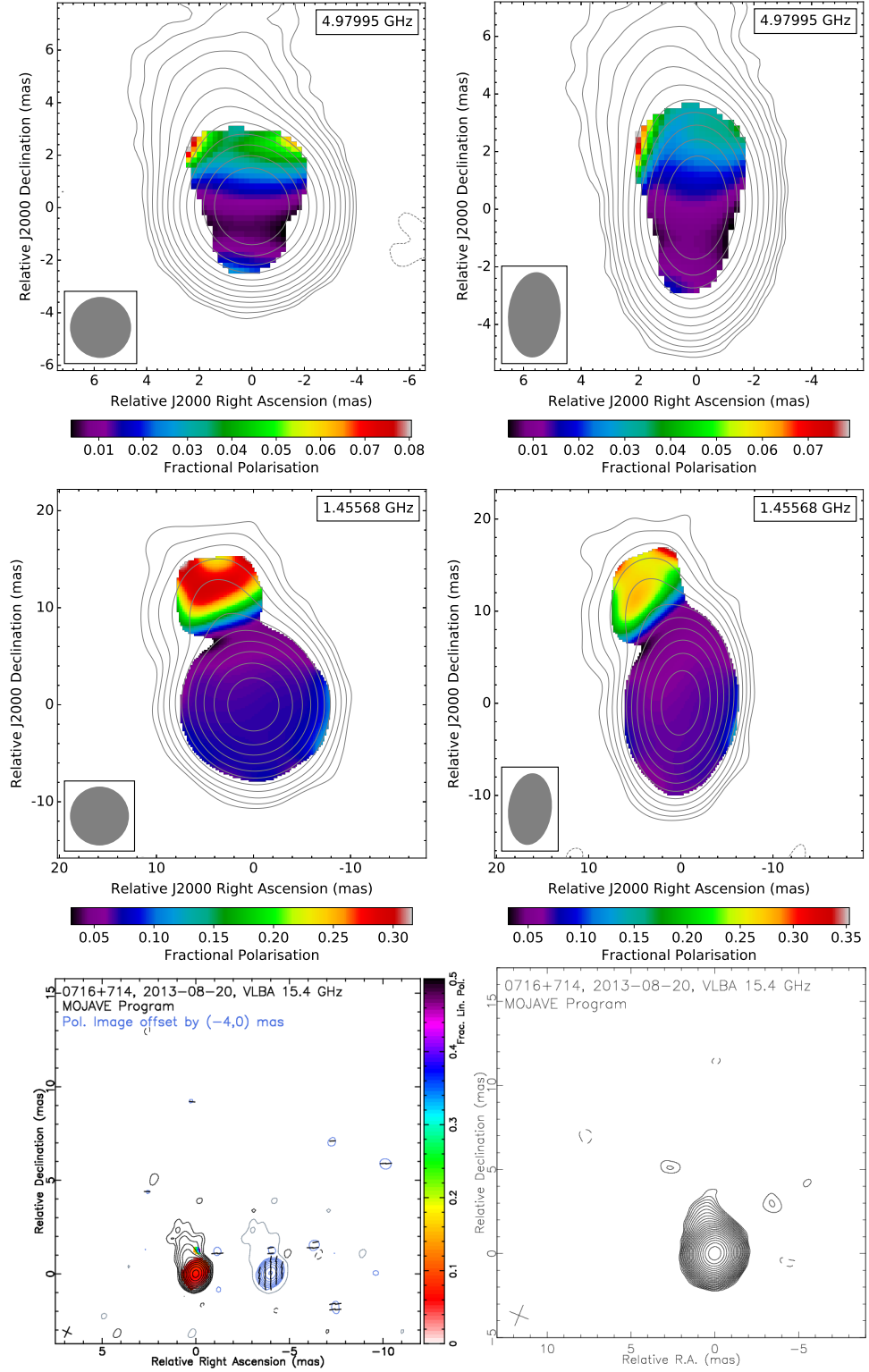


Figure 3.20: The top two panels show the 5 GHz fractional polarisation maps for J0721+7120 convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz fractional polarisation maps convolved with the 1.45 GHz beam. Polarisation intensity cutoffs are the same as in Figure 3.19. The bottom two panels show the 15 GHz MOJAVE polarisation and fractional polarisation (left) and tapered intensity (right) maps from 20/08/2013.

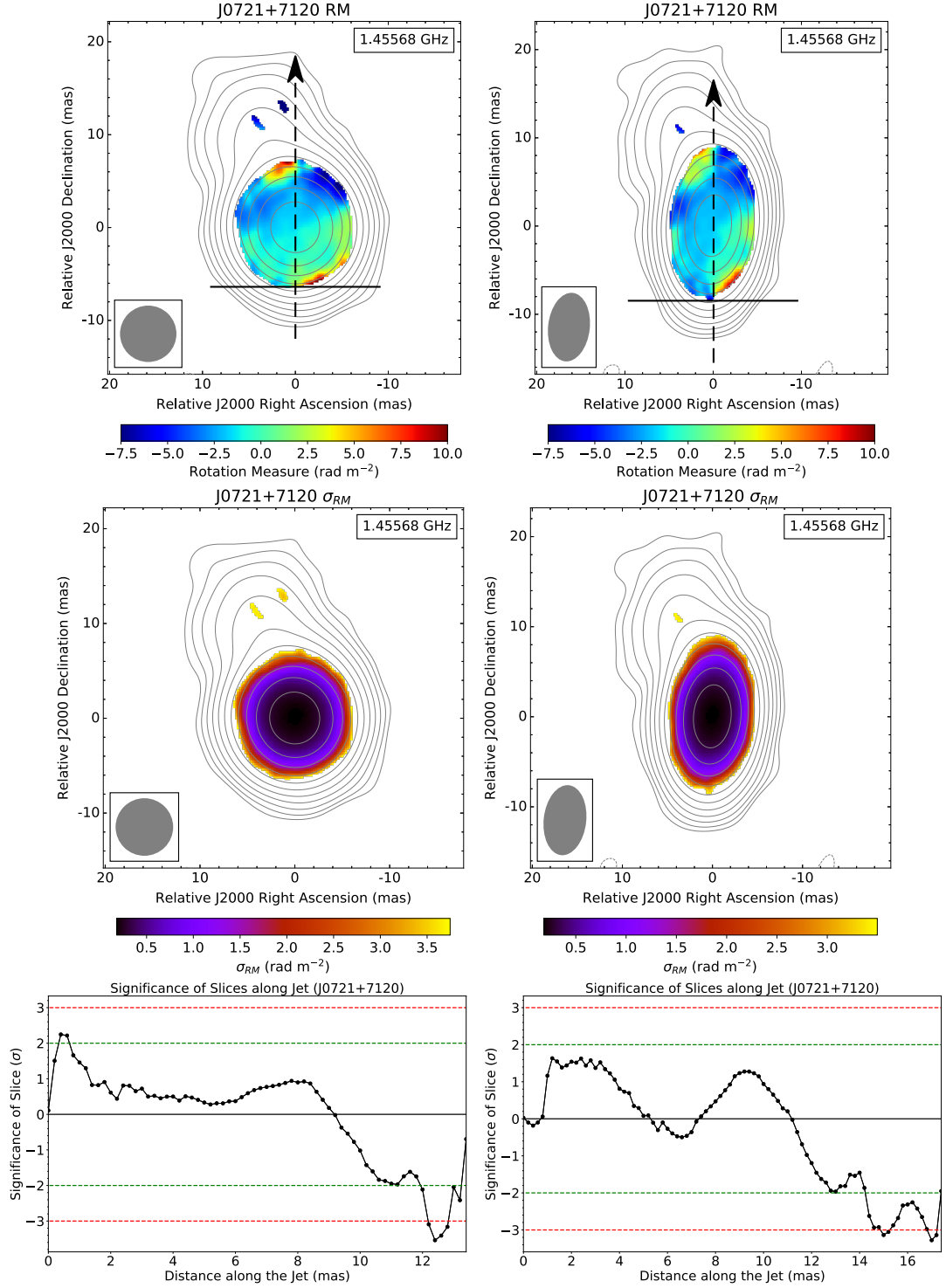


Figure 3.21: The top two panels depict the rotation measure maps for J0721+7120 convolved with the circular (left) and elliptical (right) 1.45 GHz restoring beams. The middle two panels show the corresponding error maps. The bottom two panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrow shown in the top two panels.

A study by Mahmud et al. (2013) at frequencies between 4.6 and 15.4 GHz found transverse RM gradients in both the core and the inner jet of J0721+7120. A reversal in the direction of the gradient was found between the core gradient and the jet gradient. The most simple explanation for this reversal is a nested-helix B-field structure, which involves nested helical fields surrounding the jet, one inside the other, with the directions of the azimuthal field components being opposite in the two. These two regions of helical field will be associated with oppositely directed RM gradients, and the total observed RM gradient will be determined by which region of helical field dominates the observed RMs. See Gabuzda et al. (2018) for further details of this nested structure. Another study using 18 to 22 cm data was made as part of the master's thesis of Fiona Healy (Healy 2013) wherein a distinct statistically significant gradient was found going from positive to negative west to east. The data used in that thesis will be examined again in Chapter 4.

The rotation measure maps in Figure 3.21 shows tentative evidence for transverse RM gradients towards the northern end of the RM distribution. The transverse gradients are in the same direction as the statistically significant reversal found by Mahmud et al. (2013). However, the fact that this gradient only reaches 3σ significance for a range of just a few pixels leaves this in doubt. Nevertheless, it is intriguing that the "checkerboard" pattern visible in the elliptical beam RM map resembles the pattern reported by Mahmud et al. (2013), and this may be genuine. The gradient found by Healy (2013) at a relative declination of 10 to 15 mas was unable to be verified as this RM map does not extend that far.

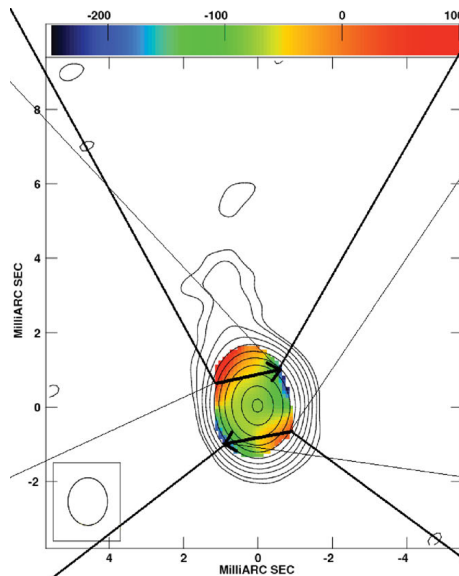


Figure 3.22: RM gradients found by Mahmud et al. (2013) using 4.6–15.4 GHz VLBA polarisation data.

3.2.5 J0738+1742

J0738+1742 (common name OI 158) has a redshift of $z = 0.45$ (Nilsson et al. 2012). As seen in the 15 GHz MOJAVE and 23 GHz RRIFD observations, as well as the intensity maps in Figure 3.23, the jet initially leaves at an angle $\theta \approx 70^\circ$ before bending dramatically to the south and arching backwards. The spectral index maps are consistent with an optically thick core, with α decreasing with distance along the jet. The core-jet gradient in the spectral-index maps is consistent with an initial jet direction of about 70° .

Previous polarisation studies such as Gabuzda et al. (1989) at 5 GHz and more recent MOJAVE studies at 15 GHz have found the projected magnetic field to be predominantly perpendicular or parallel to the jet axis at different epochs. Polarimetric VLBI observations at 22 and 43 GHz by Gomez et al. (1999) noted a twisted jet with two sharp apparent bends of 90° within 2 mas of the core. The magnetic field appears to smoothly follow one of the bends in the jet. One possible interpretation is that this is caused by the precession of the black hole at the centre of the AGN, or possible interaction between the jet and the surrounding medium.

The polarisation angle maps presented in Figure 3.24 show polarisation angles perpendicular to the jet direction along the outer edge of the jet. Both the RM_{Gal} corrected EVPAs and χ_0 maps are consistent. This is a strong indication of a longitudinal magnetic field in this part of the jet. Towards the centre of the jet, the polarised intensity is weaker, and polarisation angles appear to be orientated parallel to the axis of the jet, indicating an orthogonal magnetic field at the centre. Overall, a tentative spine-sheath structure is observed in the jet of J0738+1742, compatible with the existence of a helical magnetic field. Figure 3.25 shows maps of the fractional polarisation distribution in J0738+1742 at 5 GHz and 1.45 GHz. The degree of polarised intensity is lowest in the core, increasing close to the theoretical limit of 75% in the jet. A clear increase in fractional polarisation can be seen towards the edges of the jet, possibly giving further indication of the presence of a helical field. Further out in the jet, the fractional polarisation is significantly greater on the outer edge of the curved jet than on the inner edge. The notable bending of the jet suggests, that this increase in polarisation results from this jet curvature. As the jet bends, the plasma on the outer edge of the bend is stretched, while the plasma on the inner edge is squeezed. Assuming that magnetic field lines are "frozen in" to the plasma, the longitudinal component of the associated helical field lines will be stretched at the jet edge and squeezed in the inner edge.

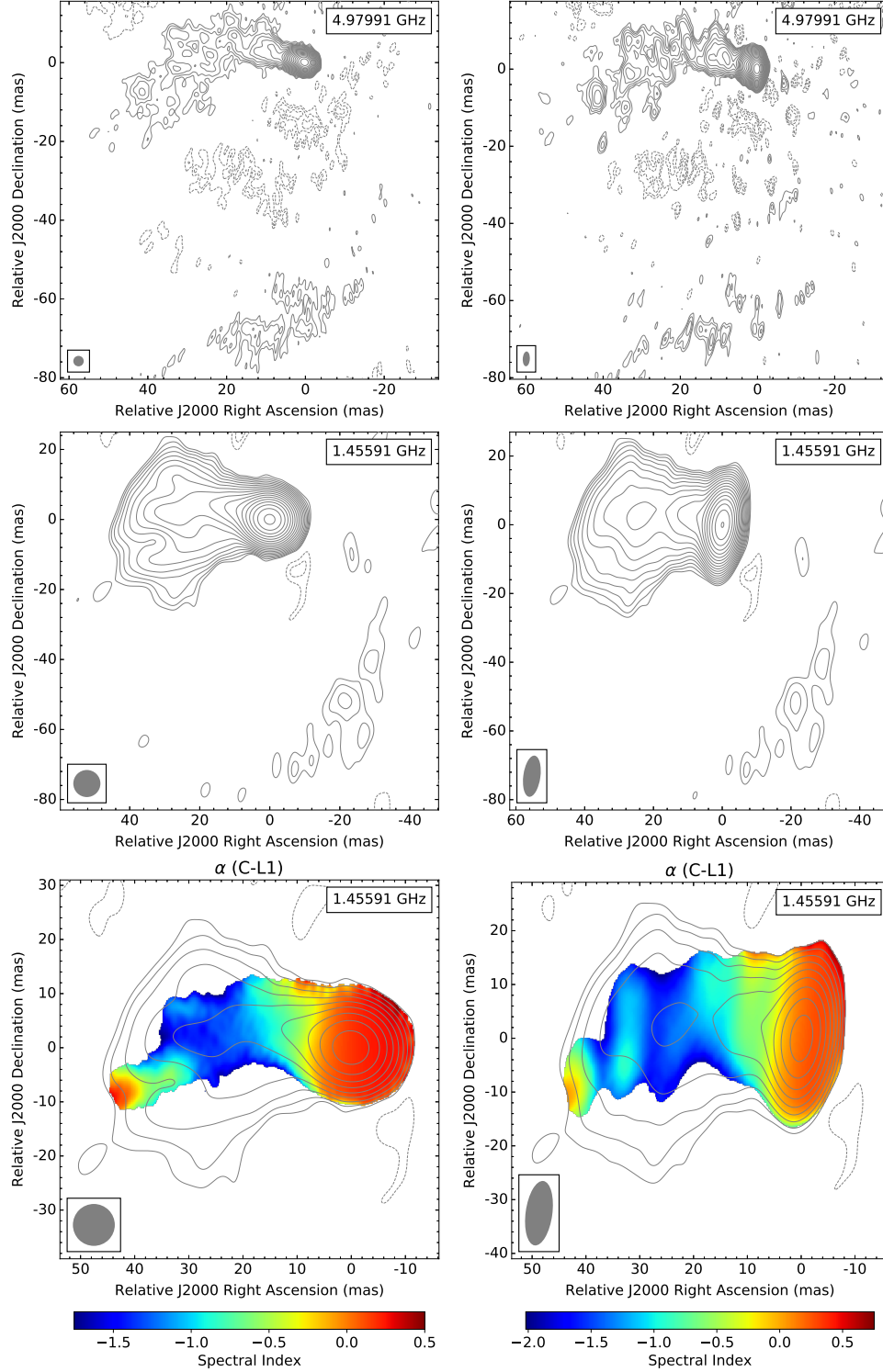


Figure 3.23: The top two panels depict the 5 GHz intensity maps for J0738+1742 convolved with the circular (left) and elliptical (right) 5 GHz beam. The middle two panels show the same for the 1.45 GHz intensity maps convolved with the 1.45 GHz beam. The bottom two panels show the C-L1 spectral index maps for J0738+1742 convolved with the 1.45 GHz beams. Intensity contours for the panels in the first two rows increase in factors of $\sqrt{2}$ and in the bottom row by factors of 2.

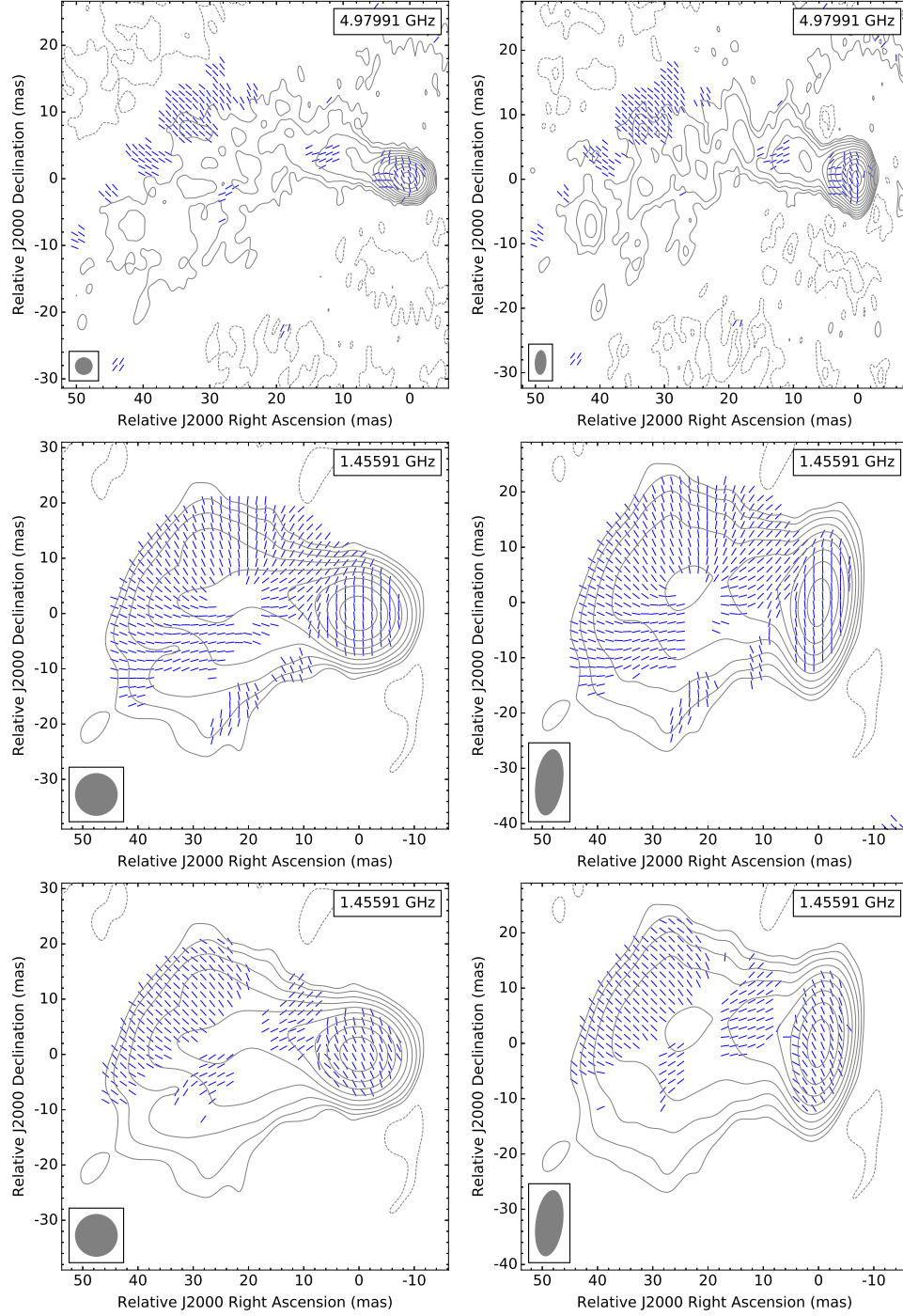


Figure 3.24: The top two panels depict the 5 GHz polarisation angle maps for J0738+1742 corrected for only the Galactic RM convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz polarisation angle maps corrected for only the Galactic RM convolved with the 1.45 GHz beam. The bottom two panels show the 1.45 GHz χ_0 maps convolved with the 1.45 GHz beams. The polarisation intensity cutoffs for the top four panels are 0.35 mJy/beam (5 GHz circular beam), 0.35 mJy/beam (5 GHz elliptical beam), 0.6 mJy/beam (1.45 GHz circular beam) and 0.6 mJy/beam (1.45 GHz elliptical beam).

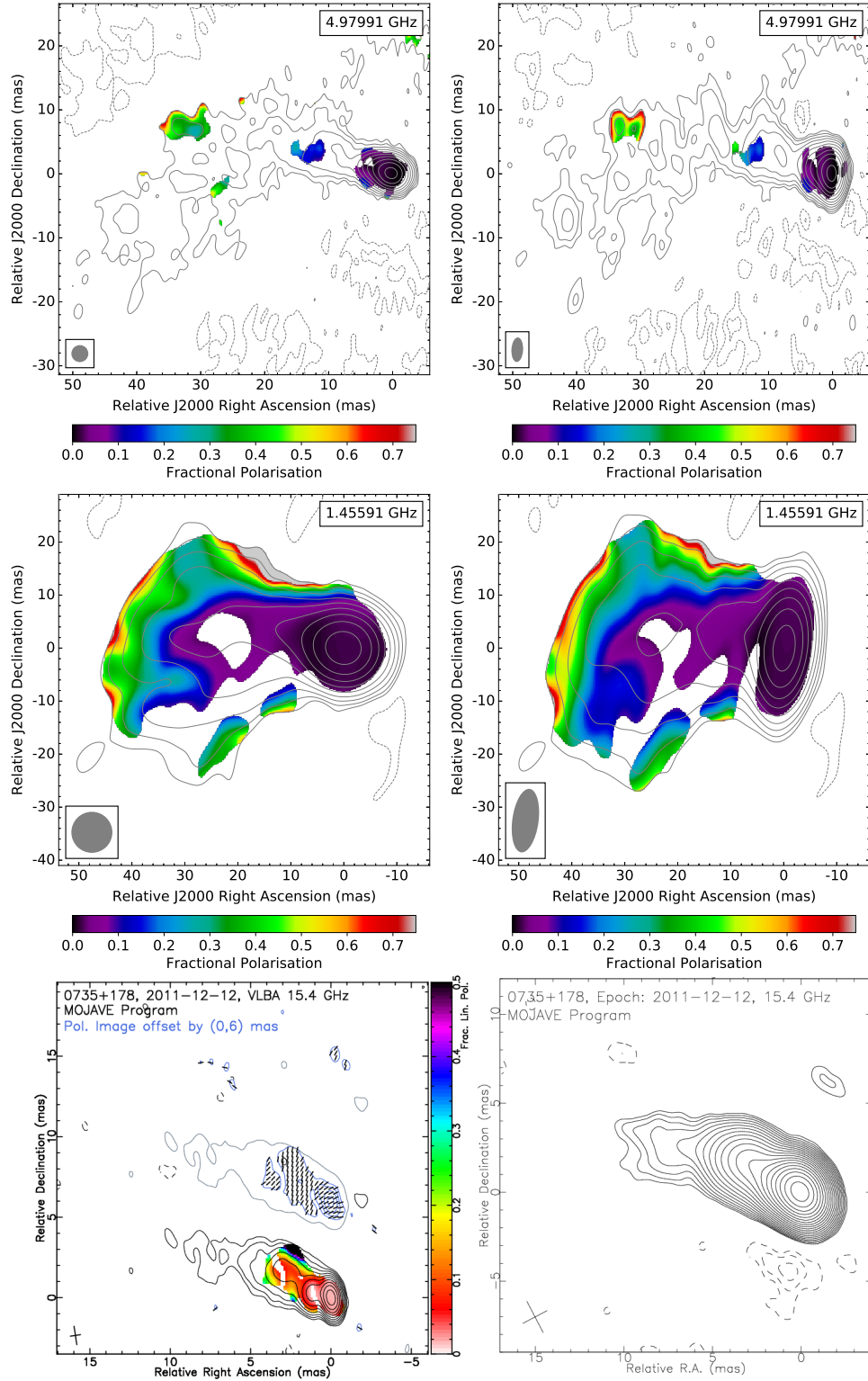


Figure 3.25: The top two panels show the 5 GHz fractional polarisation maps for J0738+1742 convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz fractional polarisation maps convolved with the 1.45 GHz beam. Polarisation intensity cutoffs are the same as in Figure 3.24. The bottom two panels show the 15 GHz MOJAVE polarisation and fractional polarisation (left) and tapered intensity (right) maps from 12/12/2011.

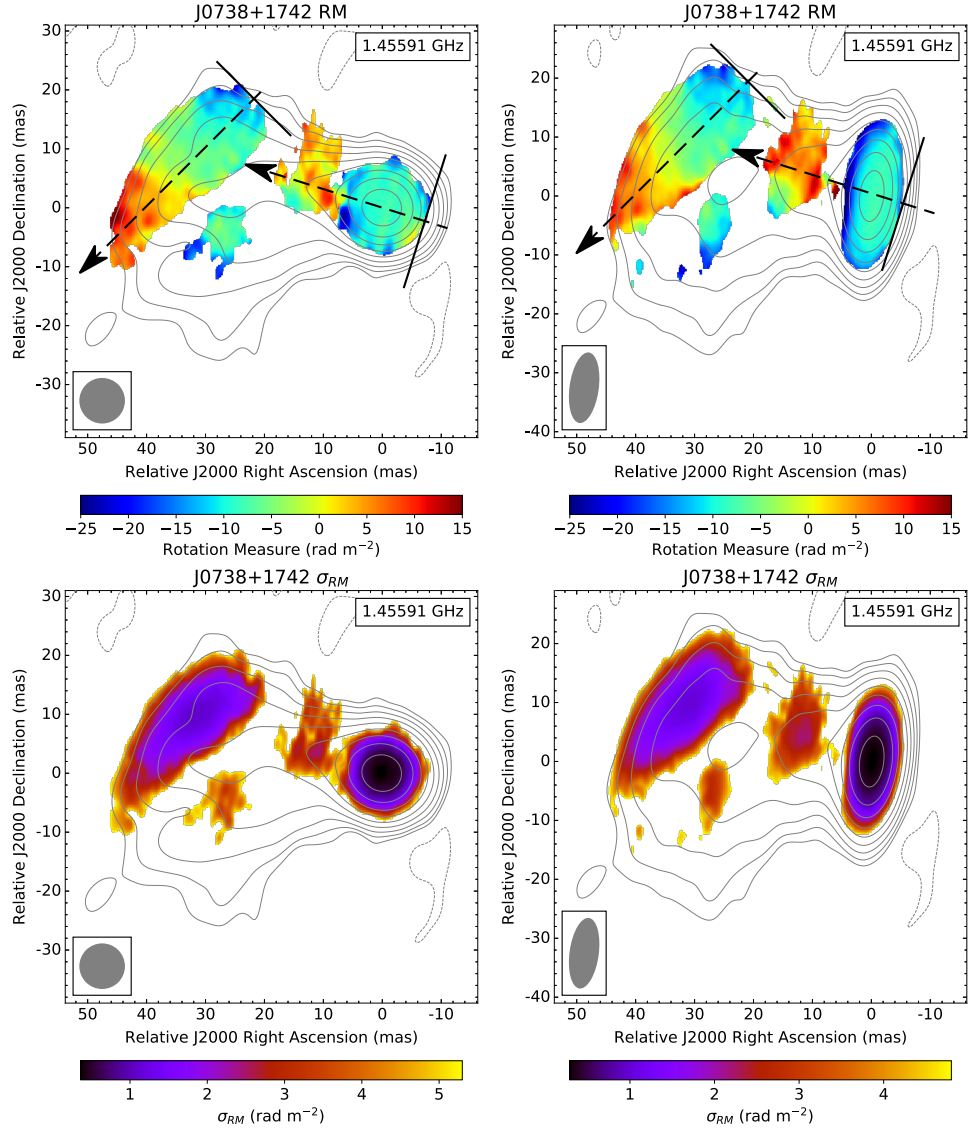


Figure 3.26: The top two panels depict the rotation measure maps for J0738+1742 convolved with the circular (left) and elliptical (right) 1.45 GHz restoring beams. The bottom two panels show the corresponding error maps.

In essence, the magnetic field would be more ordered and enhanced on the outer edge compared to the inner edge, leading to a higher degree of polarisation on the outer edge. A search was made to find significant systematic gradients, with the rotation measure maps shown in Figure 3.26. No significant transverse RM gradients were found. There is a highly significant RM gradient at the easternmost edge of the jet. Given that this is a region where the jet is bending, one possibility is that this RM gradient is due to the curvature of the jet, with the line-of-sight component of the magnetic field becoming more strongly oriented toward the Earth as the jet bends.

3.2.6 J0748+2400

J0748+2400 has a redshift of 0.409 (Schneider et al. 2010). The 15 GHz MOJAVE intensity observations and those in Figure 3.27 show the jet extends linearly to the north at roughly an angle of $\theta \approx -50^\circ$. However, the 5 GHz intensity map shows that the jet begins to bend at about 15 mas west from the core possibly due to interaction with the surrounding medium. At 1.45 GHz the maximum westerly extension is about 30 mas. The spectral index maps exhibit the expected behaviour for a partially optically thick core, with α decreasing with distance along the jet, and the core-jet spectral index gradient is consistent with the observed structural position angle of the jet.

The 15 GHz MOJAVE maps show parallel EVPA alignment with the jet up to a relative right ascension of -10 mas. Pushkarev et al. (2005) noted a possible spine-sheath structure, with innermost polarised components aligned with the jet and further out ones being almost orthogonal. In Figure 3.28, this is reflected in the χ_0 maps (bottom two panels). The polarisation angles only appear aligned with the jet near the core while the polarisation angles further out are orthogonal, following the bent jet direction displayed in the 5 GHz intensity map. The areas of parallel and perpendicular alignment suggest orthogonal and longitudinal fields predominate in their respective regions. As noted in Pushkarev et al. (2005), the polarisation structure provides good evidence for a helical magnetic field or interaction with an ambient medium surrounding the AGN.

The fractional polarisation shown in Figure 3.29 is fairly low in the core ($m < 5\%$). In the jet, the fractional polarisation increases towards the edges of the jet, peaking at around 30% on the north side at around 15 mas west. This could be associated with the jet bending mentioned earlier, with the helical field lines at the outer edge becoming more ordered than the inner edge and causing increased fractional polarisation. On the other hand, this increase could also be caused by interaction with an ambient medium. There is a slight increase compared to the centre (to $m \approx 20\%$) on the south jet side consistent with the concept of a helical field regardless of bending. The rotation measure maps in Figure 3.30 show consistent statistically significant gradients both in the core, where the significance exceeds 5σ , and further out in the jet where it exceeds 3σ . This provides good evidence for a toroidal or helical field component. A 2–6 cm map by Gabuzda et al. (2004) for J0748+2400 shows a transverse RM gradient in the opposite direction on smaller scales and there may be a hint of this reversal on the left-hand side of the RM distribution. This was confirmed with a significance of 4σ in (Gabuzda et al. 2015).

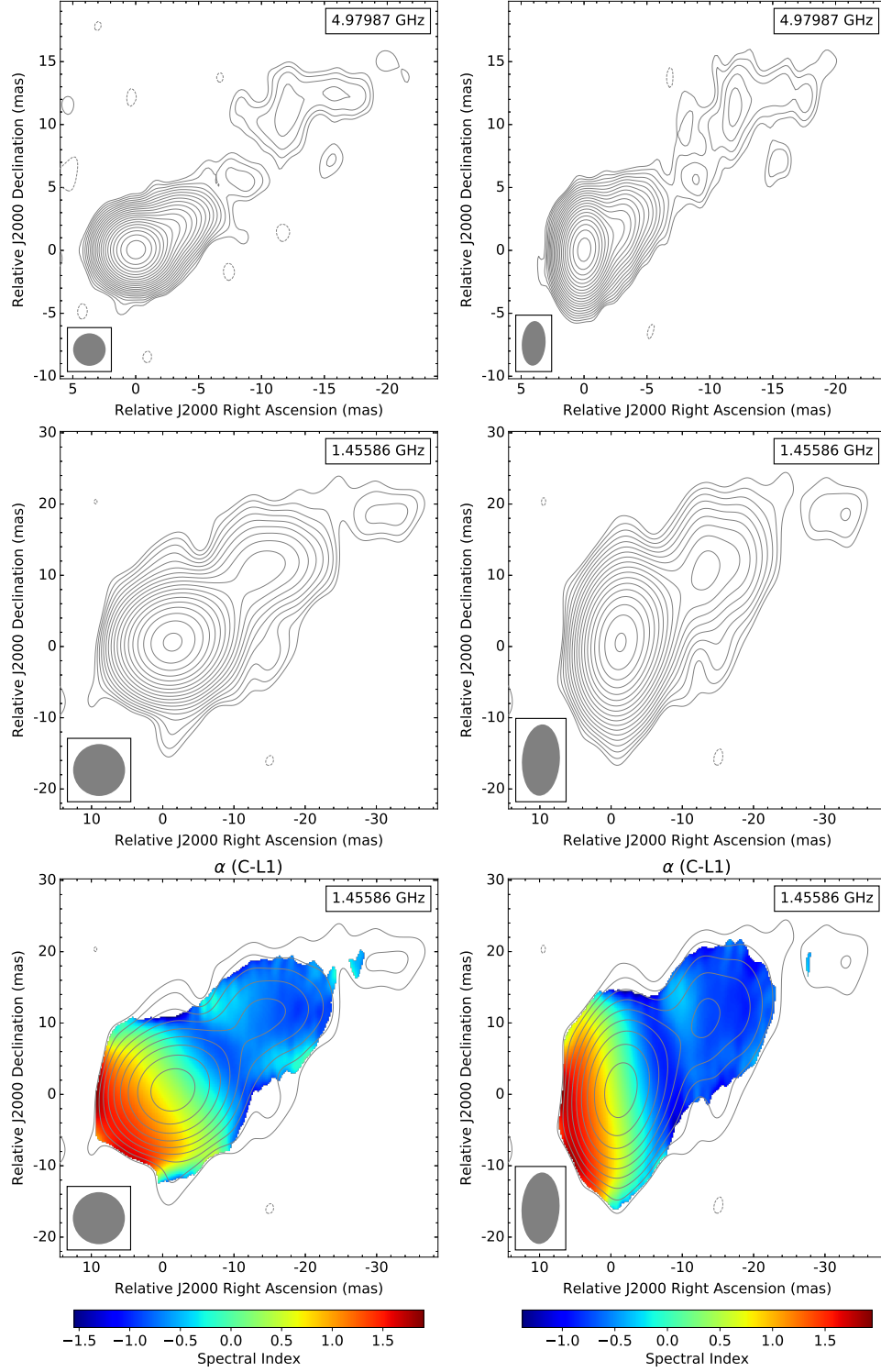


Figure 3.27: The top two panels depict the 5 GHz intensity maps for J0748+200 convolved with the circular (left) and elliptical (right) 5 GHz beam. The middle two panels show the same for the 1.45 GHz intensity maps convolved with the 1.45 GHz beam. The bottom two panels show the C-L1 spectral index maps for J0748+2400 convolved with the 1.45 GHz beams. Intensity contours for the panels in the first two rows increase in factors of $\sqrt{2}$ and in the bottom row by factors of 2.

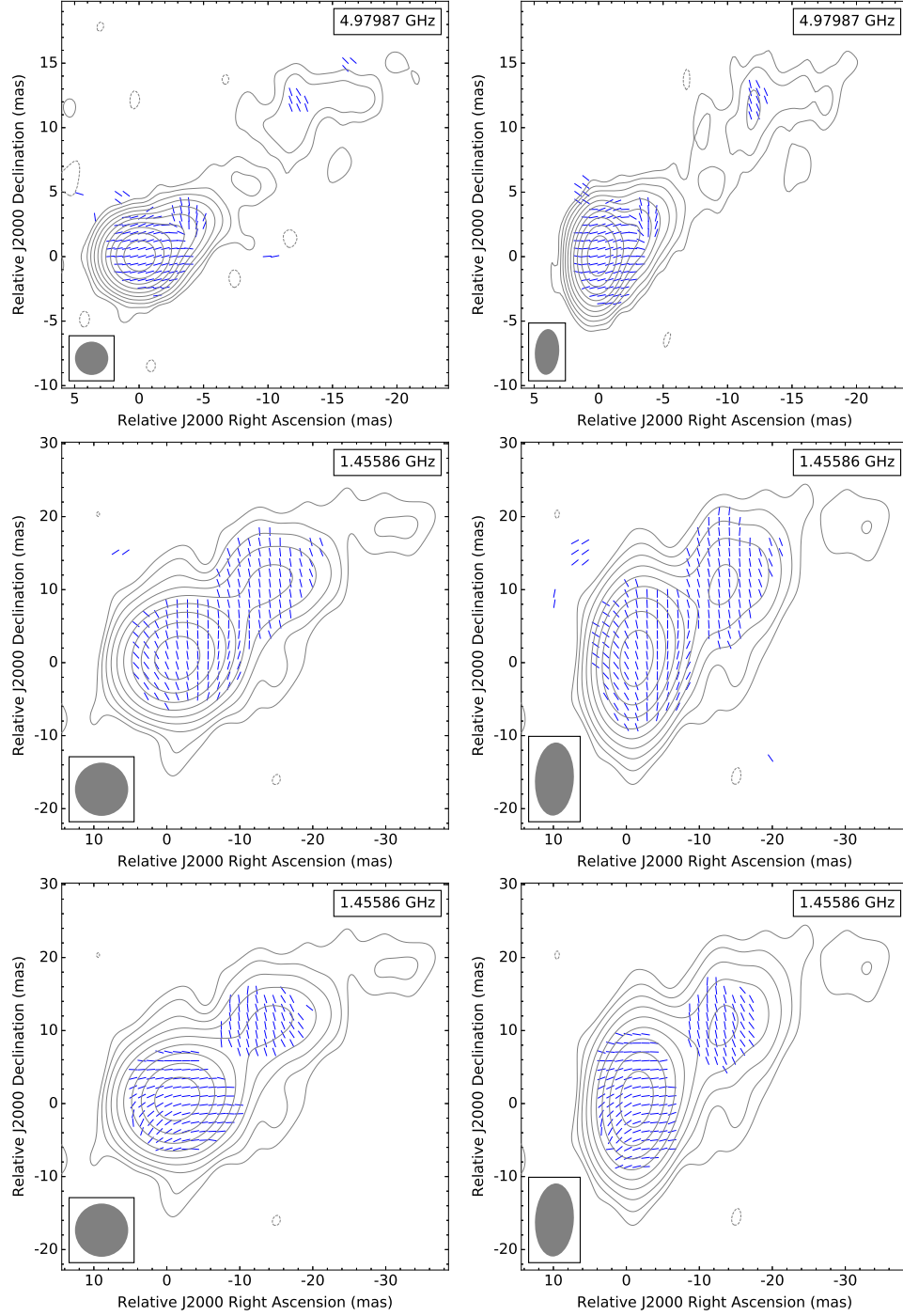


Figure 3.28: The top two panels depict the 5 GHz polarisation angle maps for J0748+2400 corrected for only the Galactic RM convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz polarisation angle maps corrected for only the Galactic RM convolved with the 1.45 GHz beam. The bottom two panels show the 1.45 GHz χ_0 maps convolved with the 1.45 GHz beams. The polarisation intensity cutoffs for the top four panels are 0.35 mJy/beam (5 GHz circular beam), 0.375 mJy/beam (5 GHz elliptical beam), 0.425 mJy/beam (1.45 GHz circular beam) and 0.4 mJy/beam (1.45 GHz elliptical beam).

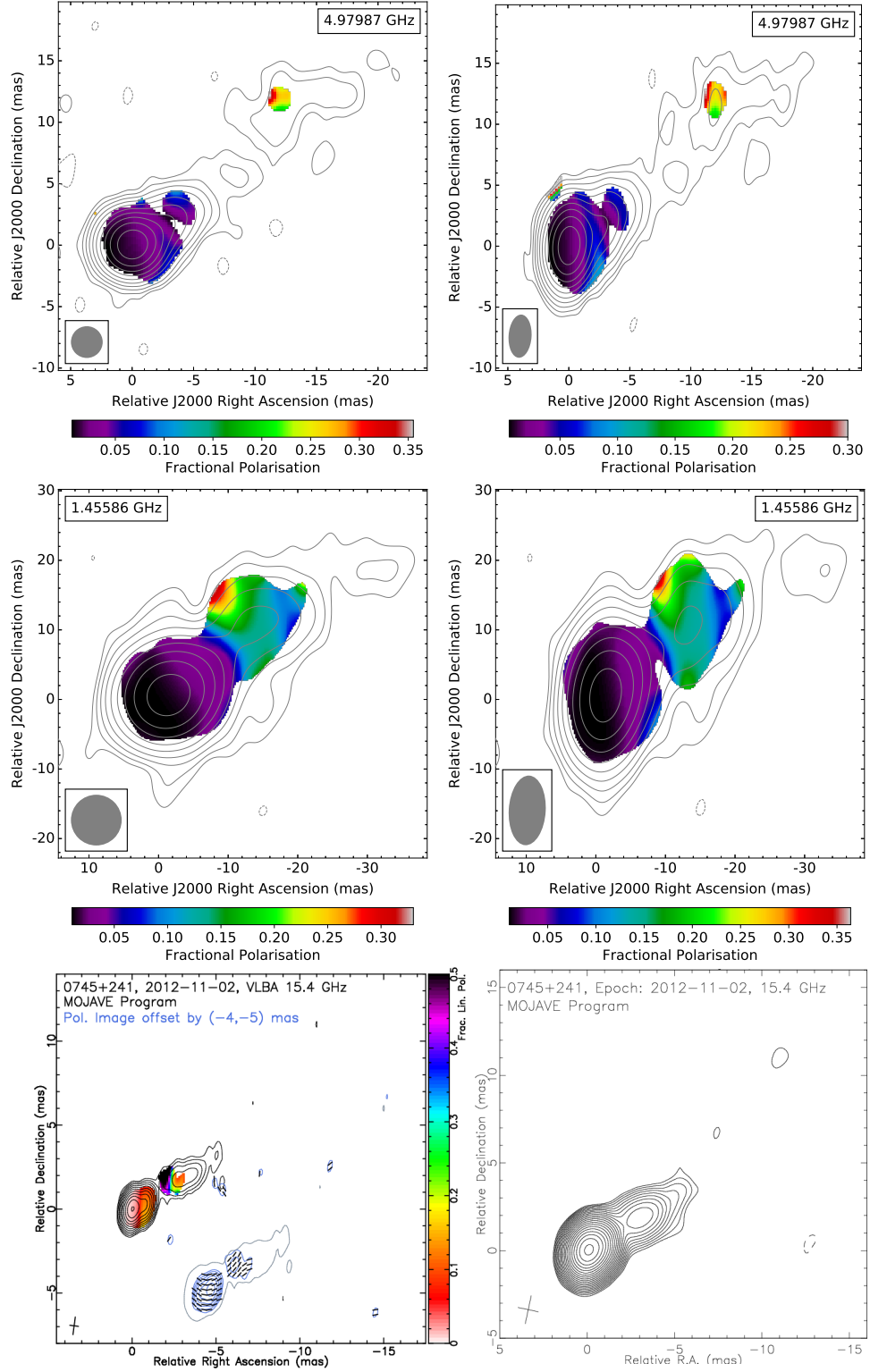


Figure 3.29: The top two panels show the 5 GHz fractional polarisation maps for J0748+2400 convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz fractional polarisation maps convolved with the 1.45 GHz beam. Polarisation intensity cutoffs are the same as in Figure 3.28. The bottom two panels show the 15 GHz MOJAVE polarisation and fractional polarisation (left) and tapered intensity (right) maps from 02/11/2012.

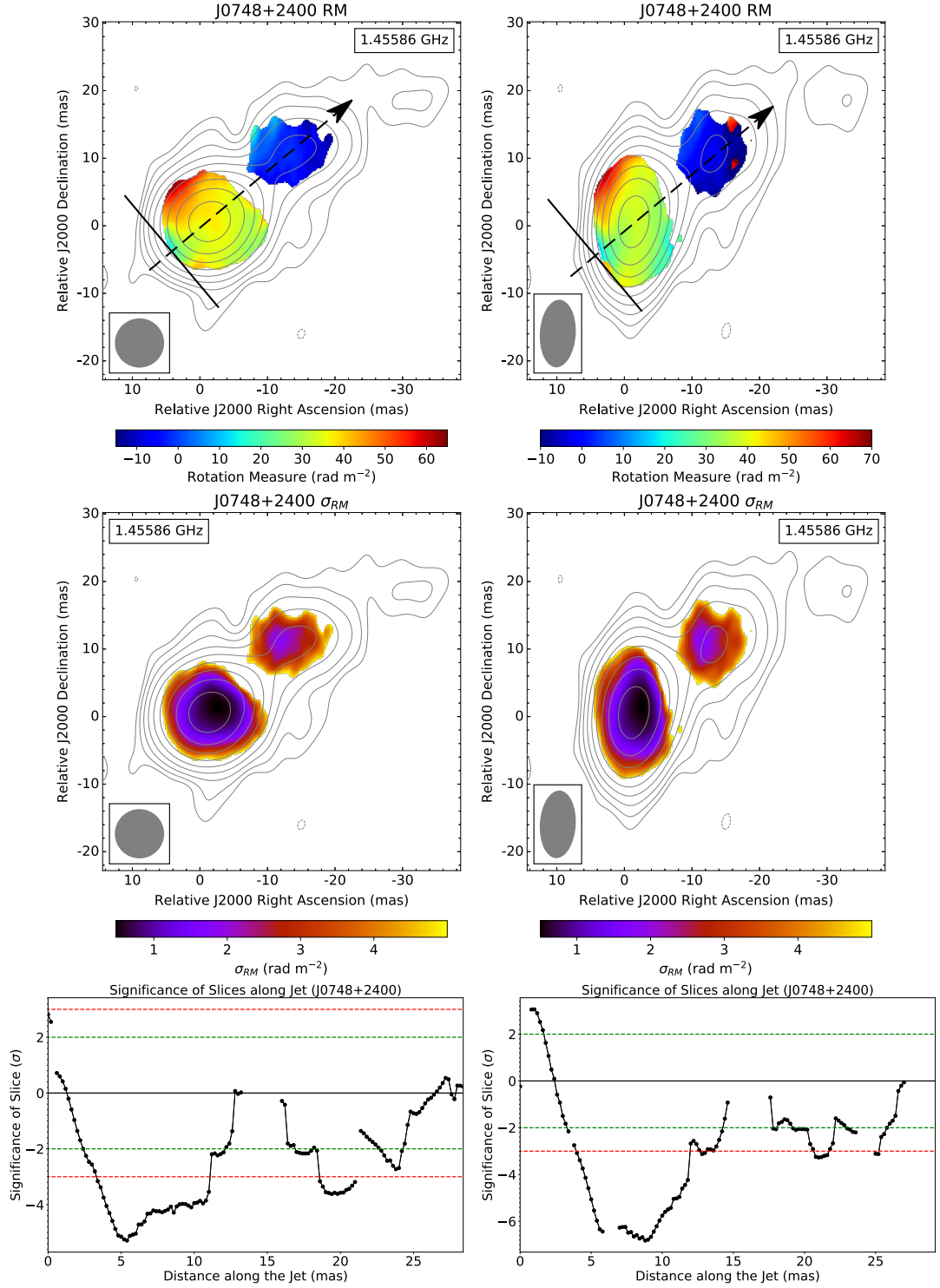


Figure 3.30: The top two panels depict the rotation measure maps for J0748+2400 convolved with the circular (left) and elliptical (right) 1.45 GHz restoring beams. The middle two panels show the corresponding error maps. The bottom two panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrow shown in the top two panels.

3.2.7 J0818+4222

J0818+4222 has a redshift $0.75 < z < 2.47$, (Sbarufatti et al. 2005, Shaw et al. 2013) The intensity maps shown in Figure 3.31, as well as in previous studies such as 5 GHz observations by Aaron (1999), show that the jet flows east before bending south and becoming diffuse. Smaller-scale observations such as the MOJAVE 15 GHz and 43 GHz VLBA polarisation observations by Lister (2001), show that the jet lies roughly in a position angle $\theta = 90^\circ$. The spectral index map shown is consistent with a partially optically thick core and optically thin jet.

Previous polarisation observations of J0818+4222, such as the 15 GHz MOJAVE maps, Lister (2001) and Hovatta et al. (2012)'s χ_0 map show the polarisation angles remain aligned with the jet for the first few milliarcseconds, signifying locally orthogonal magnetic field. The 5 GHz RM_{Gal} corrected EVPAs and χ_0 maps in Figure 3.32, which cover a much larger scale, are consistent with this and stay aligned parallel to the jet as it bends. Also, the 1.45 GHz RM_{Gal} corrected EVPAs (middle panels) are transverse to the jet at a relative right ascension of 10 mas. This region seems to bend with the jet and possibly be indicative of a spine-sheath structure.

As expected, the fractional polarisation maps in Figure 3.33 show fairly low polarisation in the core. The 5 GHz fractional polarisation maps tentatively show an increase in polarisation towards the edge of the jet, consistent with a helical magnetic field.

The rotation measure maps in Figure 3.34 show a transverse RM gradient at a relative right ascension of -8 to 0 mas (positive to negative, north to south). After this, there is a distinct gradient (greater than 5σ) in the opposite direction. If this is genuine it would be a transverse RM gradient reversal.

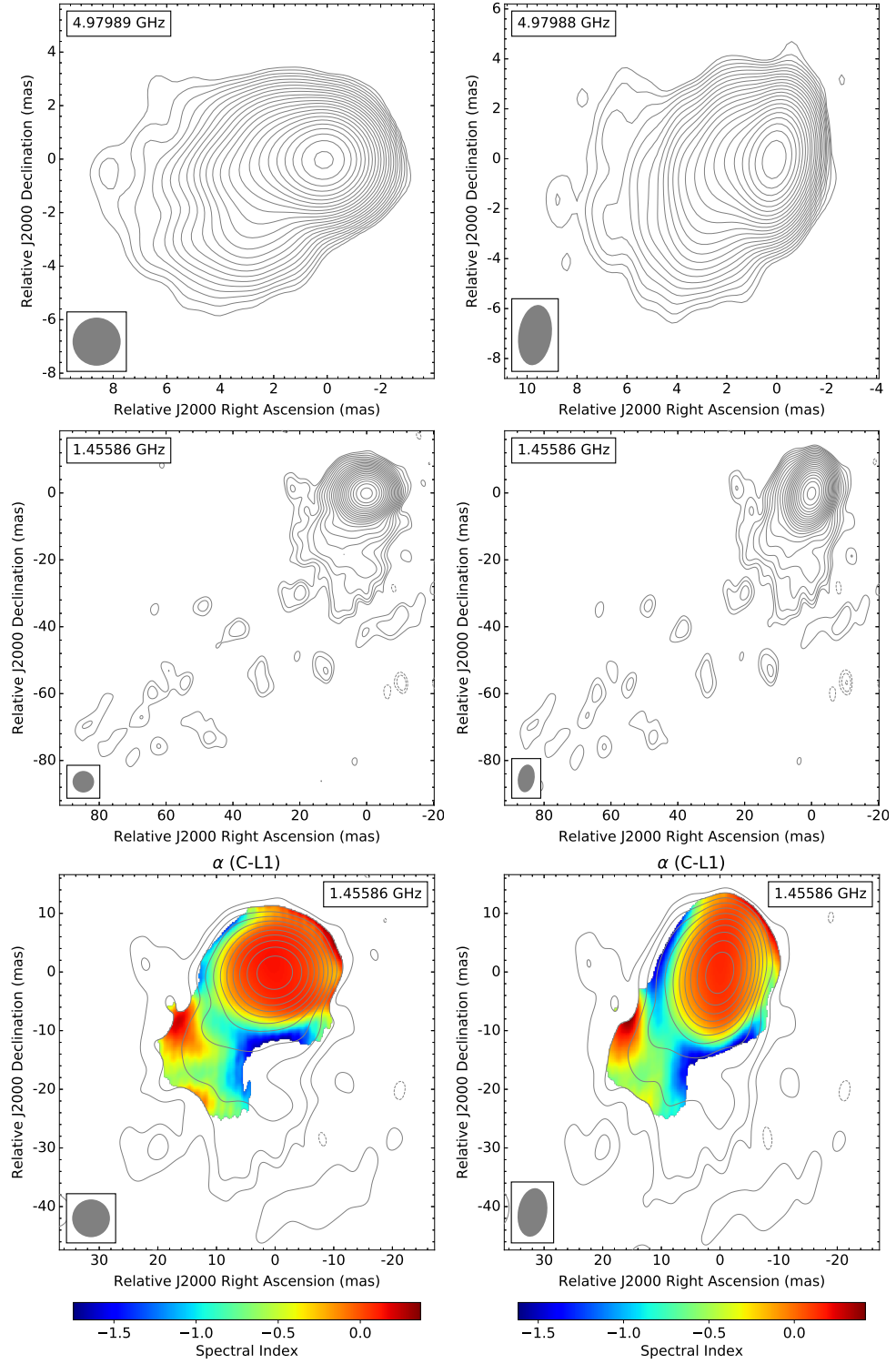


Figure 3.31: The top two panels depict the 5 GHz intensity maps for J0818+4222 convolved with the circular (left) and elliptical (right) 5 GHz beam. The middle two panels show the same for the 1.45 GHz intensity maps convolved with the 1.45 GHz beam. The bottom two panels show the C-L1 spectral index maps for J0818+4222 convolved with the 1.45 GHz beams. Intensity contours for the panels in the first two rows increase in factors of $\sqrt{2}$ and in the bottom row by factors of 2.

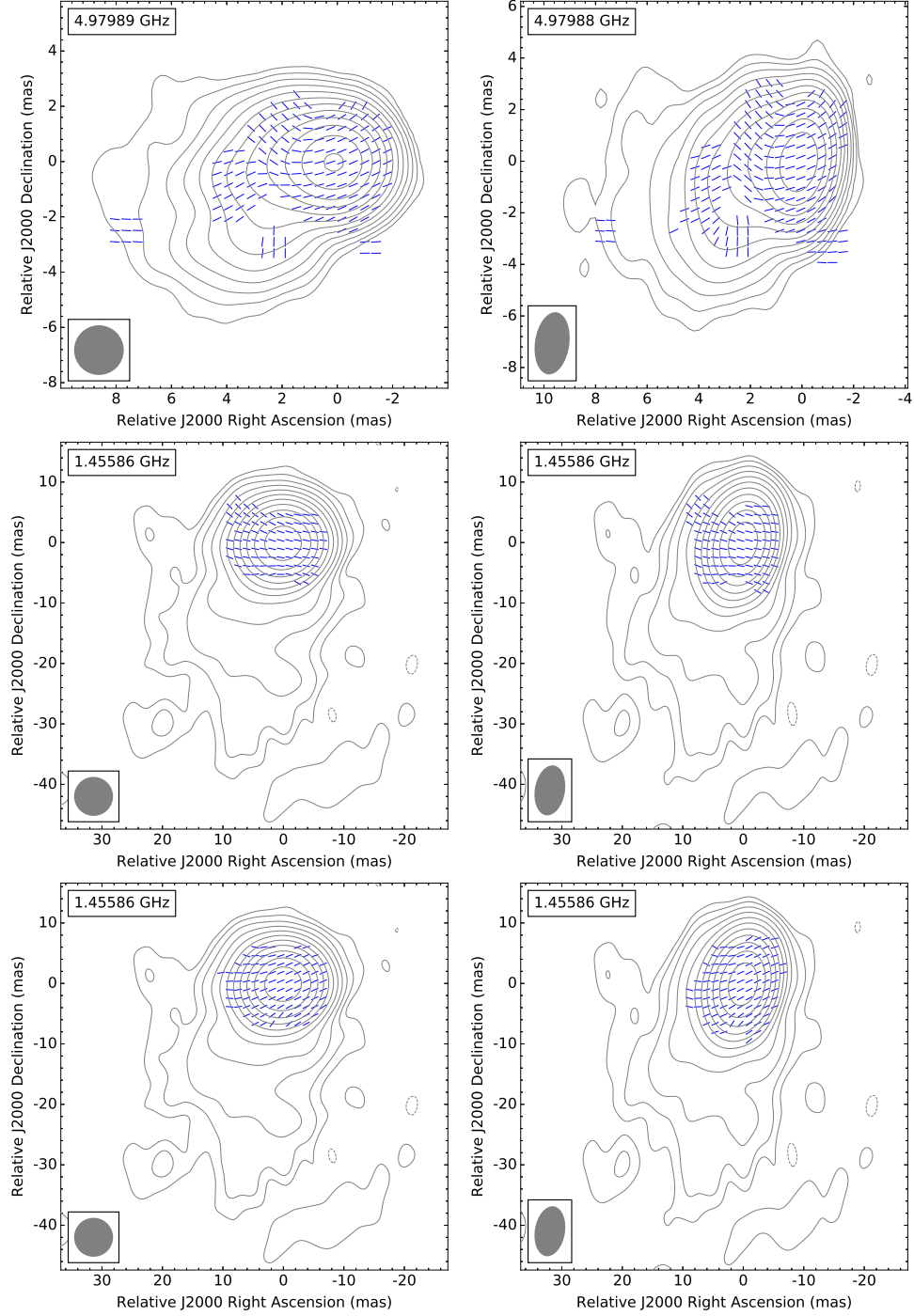


Figure 3.32: The top two panels depict the 5 GHz polarisation angle maps for J0818+4222 corrected for only the Galactic RM convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz polarisation angle maps corrected for only the Galactic RM convolved with the 1.45 GHz beam. The bottom two panels show the 1.45 GHz χ_0 maps convolved with the 1.45 GHz beams. The polarisation intensity cutoffs for the top four panels are 0.45 mJy/beam (5 GHz circular beam), 0.55 mJy/beam (5 GHz elliptical beam), 1 mJy/beam (1.45 GHz circular beam) and 1 mJy/beam (1.45 GHz elliptical beam).

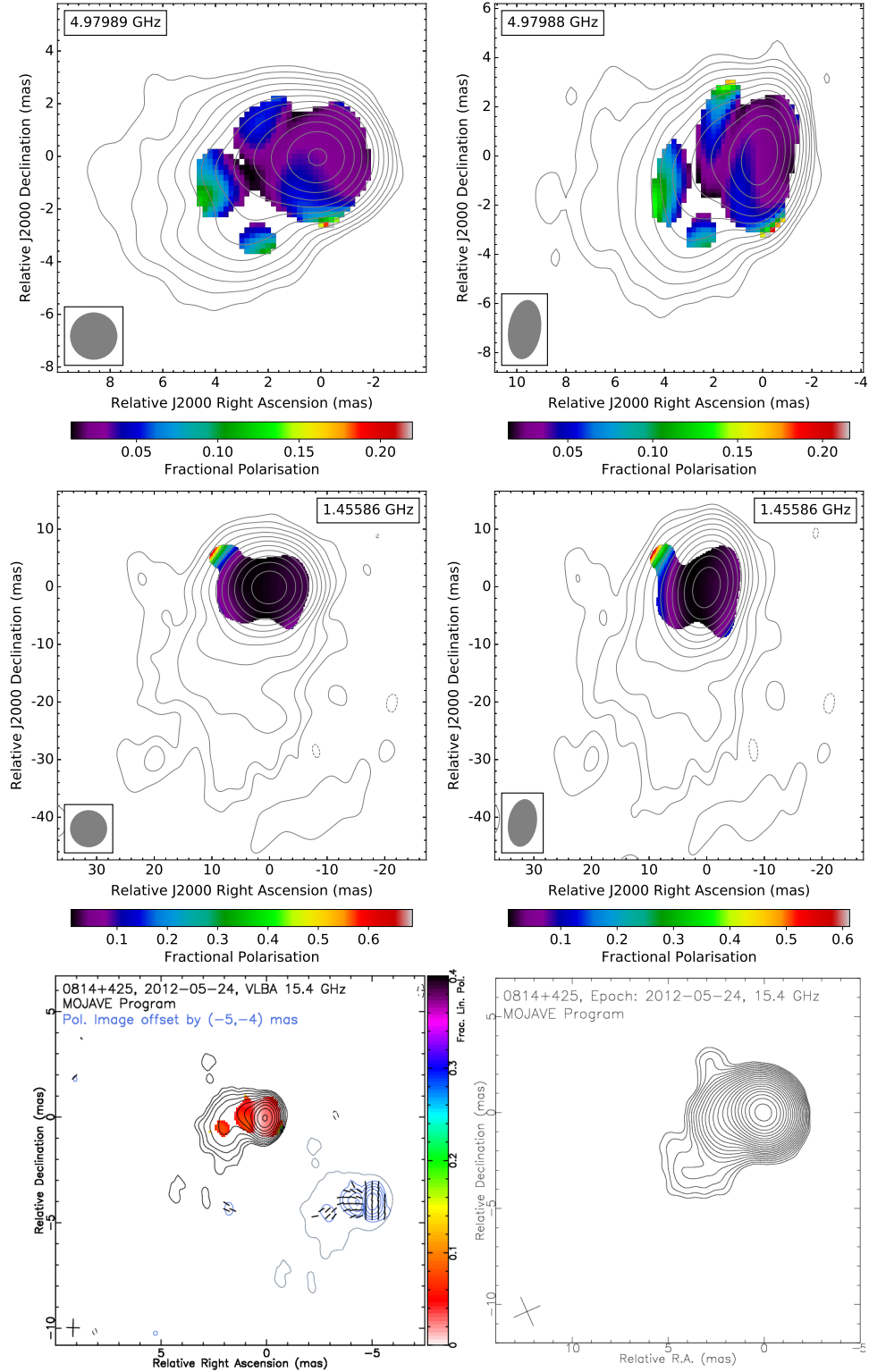


Figure 3.33: The top two panels show the 5 GHz fractional polarisation maps for J0818+4222 convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz fractional polarisation maps convolved with the 1.45 GHz beam. Polarisation intensity cutoffs are the same as in Figure 3.32. The bottom two panels show the 15 GHz MOJAVE polarisation and fractional polarisation (left) and tapered intensity (right) maps from 24/05/2012.

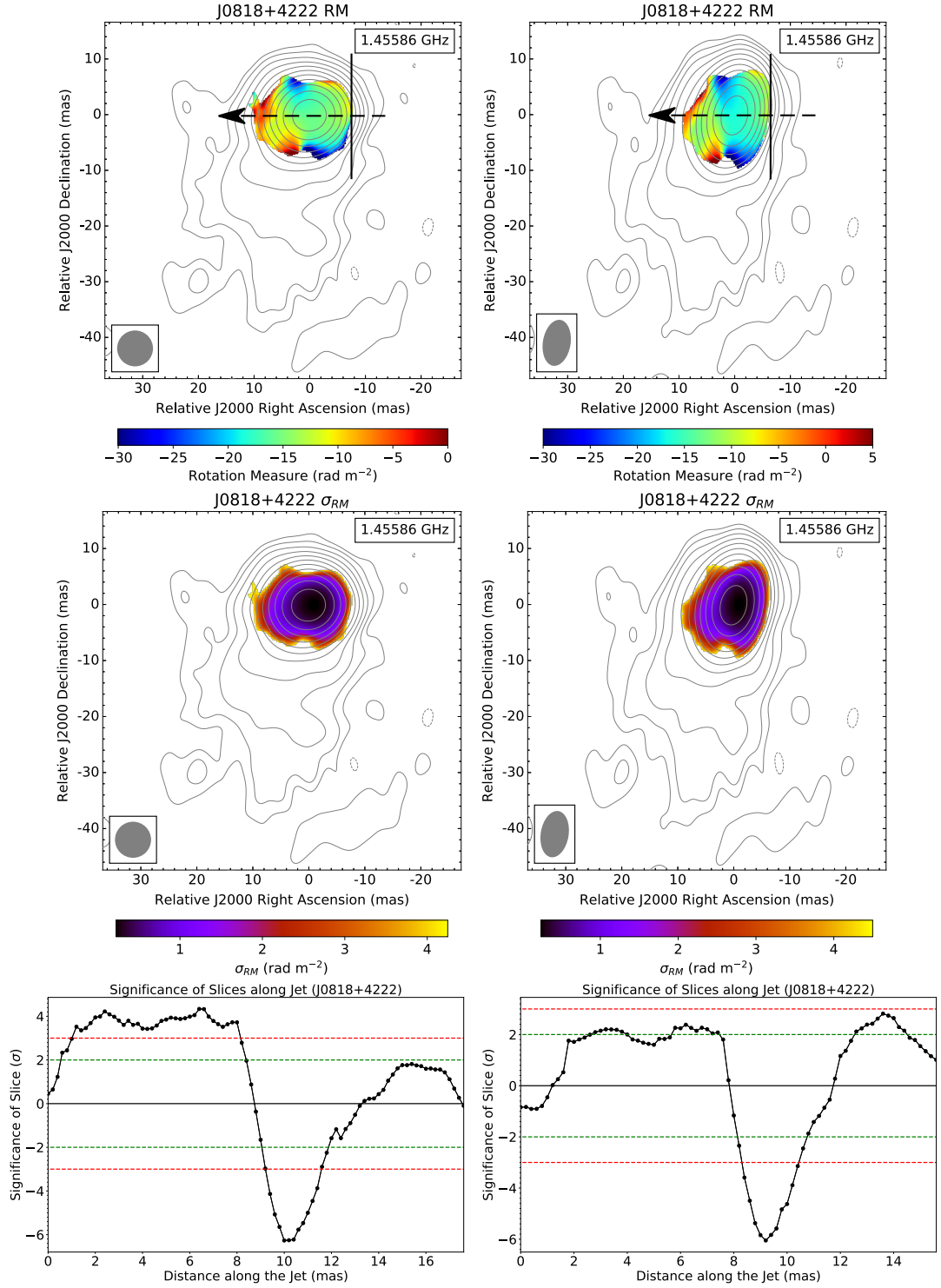


Figure 3.34: The top two panels depict the rotation measure maps for J0818+4222 convolved with the circular (left) and elliptical (right) 1.45 GHz restoring beams. The middle two panels show the corresponding error maps. The bottom two panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrow shown in the top two panels.

3.2.8 J0825+0309

J0825+0309 has a redshift of $z = 0.505$ (Shaw et al. 2013). The intensity maps shown in Figure 3.35 show a jet extending 20 mas north. Smaller-scale observations such as the 15 GHz MOJAVE observations show that the jet initially emerges at a position angle $\theta \approx 20^\circ$. The spectral index map shown is consistent with a partially optically thick core and optically thin jet, and the core-jet gradient in the spectral-index map is consistent with this jet direction.

The polarisation angles in Figure 3.36 are dominated by the core region where the polarisation is roughly orthogonal to the jet direction. The relation between the polarisation and the jet direction further out is not obvious. Previous 15 GHz observations from the MOJAVE program and also by Gabuzda & Pushkarev (2001) show that the polarisation angles generally remain aligned with the jet up to a relative declination of 5 mas but that is not evident in these observations, which are dominated by the core region.

The fractional polarisation maps in Figure 3.37 show values ranging from 0 to 20% in the core region. At 1.45 GHz (middle panels) there is a one-sided increase in polarisation at a relative declination of 10 mas. This may be a result of bending in the jet or interaction with an ambient medium. However, this structure is not shown clearly in the 1.45 GHz elliptical beam map which leaves its authenticity in doubt.

As shown in Figure 3.38, there is a possible transverse RM gradient in J0825+0309 going negative to positive, east to west. Although this gradient formally exceeds 3σ , it is dependent on a small number of edge pixels and may be spurious. Previously, a statistically significant rotation measure gradient was detected in Gabuzda et al. (2015) with data between 8.1 and 15.2 GHz. The gradient direction is the opposite of that reported here. If indeed the gradient here is not spurious this may be an example of a RM reversal. To help clarify the situation, RM maps convolved with the 2.2 GHz beam were made, the results of which are shown in Figure 3.39. The 2.2 GHz beam RM maps show the same RM structure is present and again that the transverse RM gradients detected are not monotonic, arising instead from a thin band of edge pixels, confirming that this gradient is spurious.

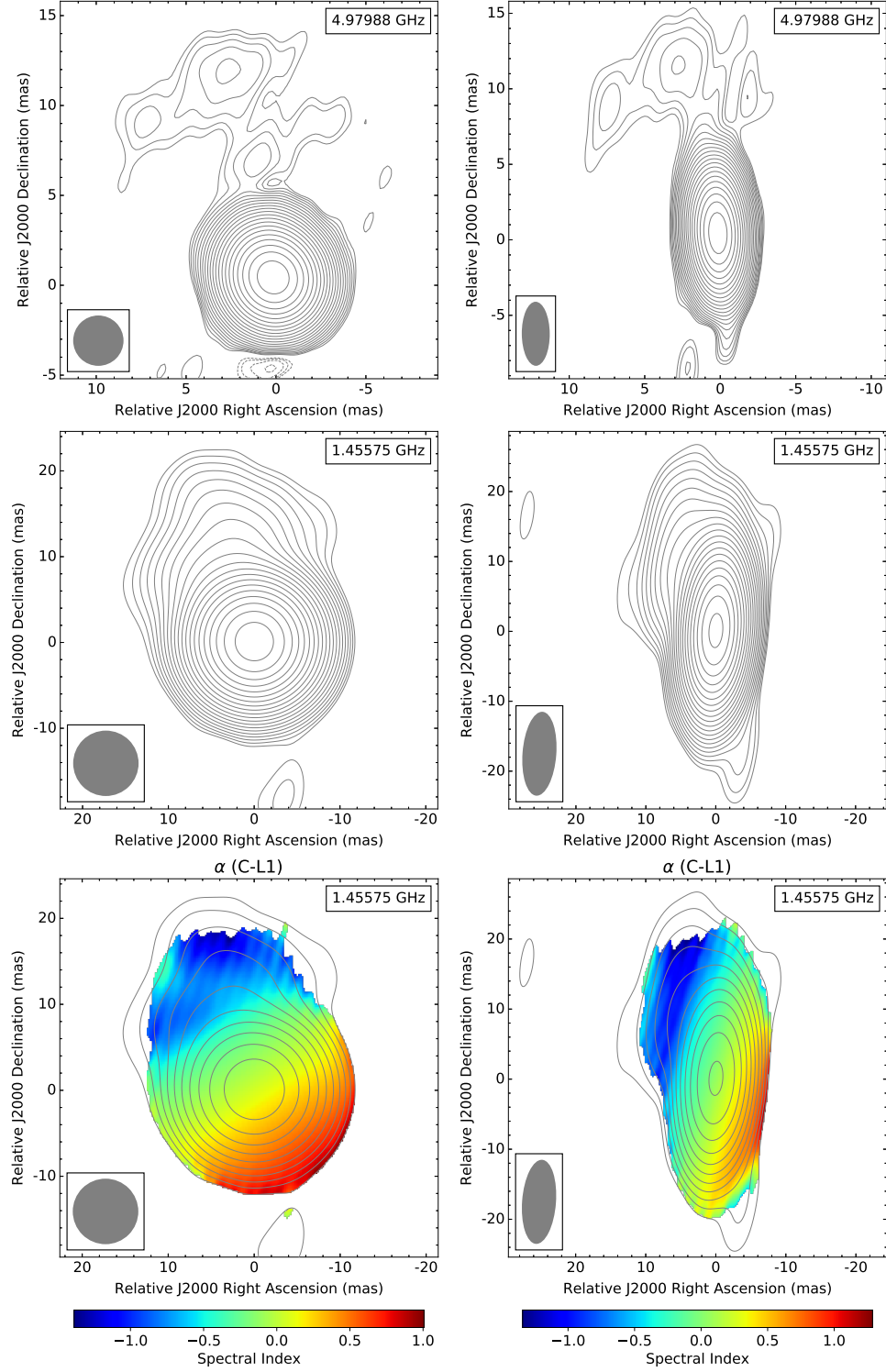


Figure 3.35: The top two panels depict the 5 GHz intensity maps for J0825+0309 convolved with the circular (left) and elliptical (right) 5 GHz beam. The middle two panels show the same for the 1.45 GHz intensity maps convolved with the 1.45 GHz beam. The bottom two panels show the C-L1 spectral index maps for J0825+0309 convolved with the 1.45 GHz beams. Intensity contours for the panels in the first two rows increase in factors of $\sqrt{2}$ and in the bottom row by factors of 2.

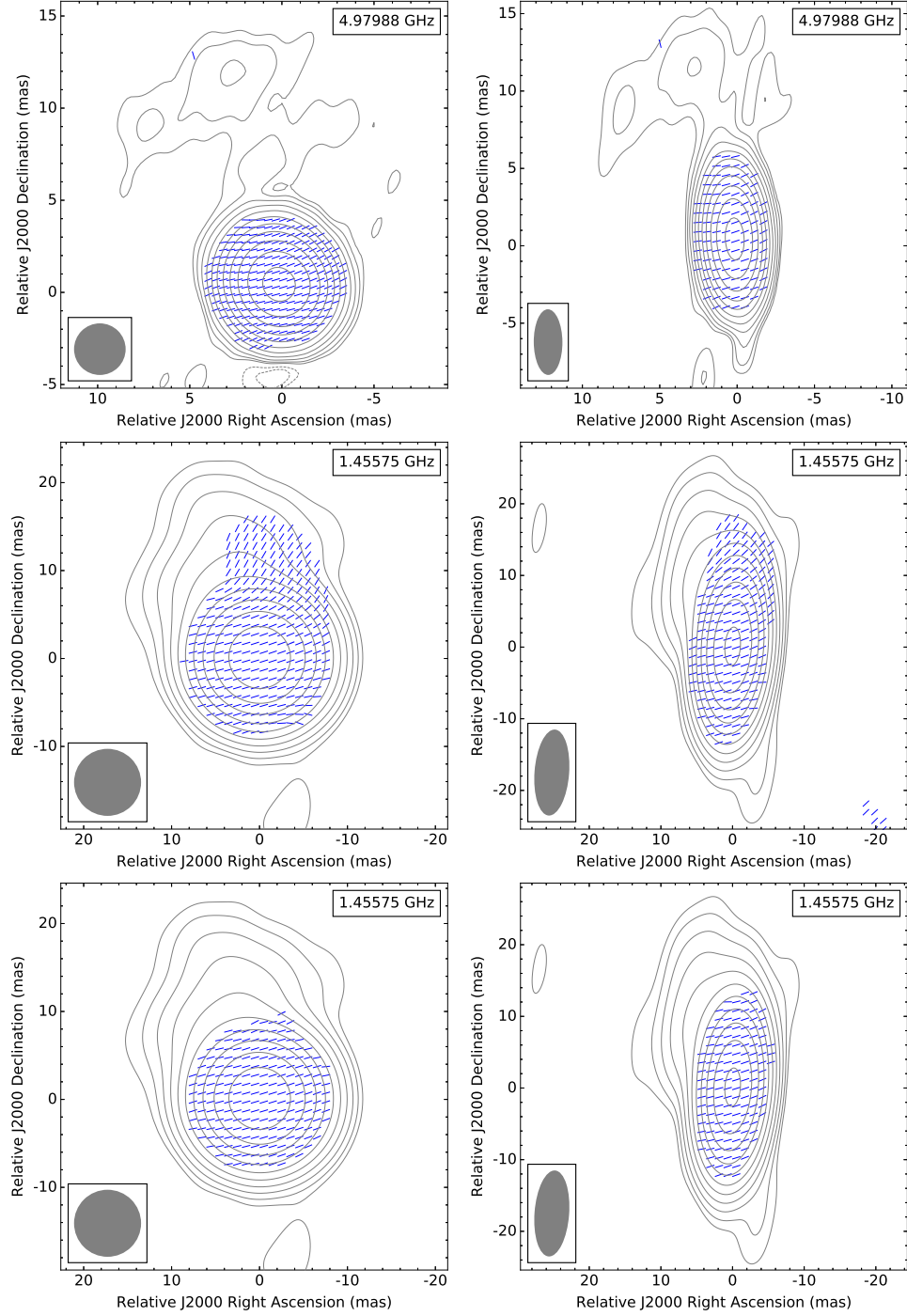


Figure 3.36: The top two panels depict the 5 GHz polarisation angle maps for J0825+0309 corrected for only the Galactic RM convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz polarisation angle maps corrected for only the Galactic RM convolved with the 1.45 GHz beam. The bottom two panels show the 1.45 GHz χ_0 maps convolved with the 1.45 GHz beams. The polarisation intensity cutoffs for the top four panels are 0.8 mJy/beam (5 GHz circular beam), 0.8 mJy/beam (5 GHz elliptical beam), 1.2 mJy/beam (1.45 GHz circular beam) and 1.225 mJy/beam (1.45 GHz elliptical beam).

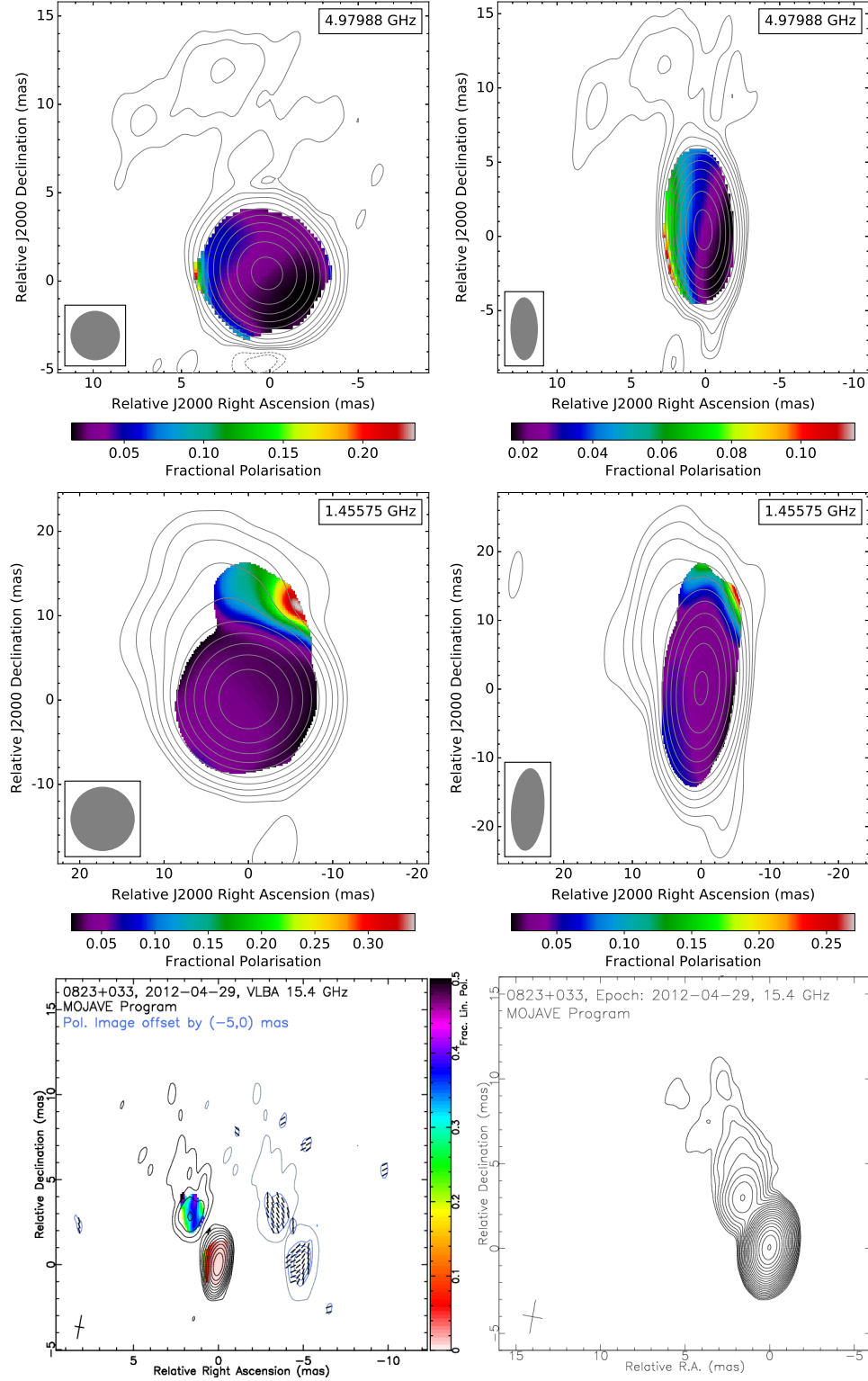


Figure 3.37: The top two panels show the 5 GHz fractional polarisation maps for J0825+0309 convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz fractional polarisation maps convolved with the 1.45 GHz beam. Polarisation intensity cutoffs are the same as in Figure 3.36. The bottom two panels show the 15 GHz MOJAVE polarisation and fractional polarisation (left) and tapered intensity (right) maps from 29/04/2012.

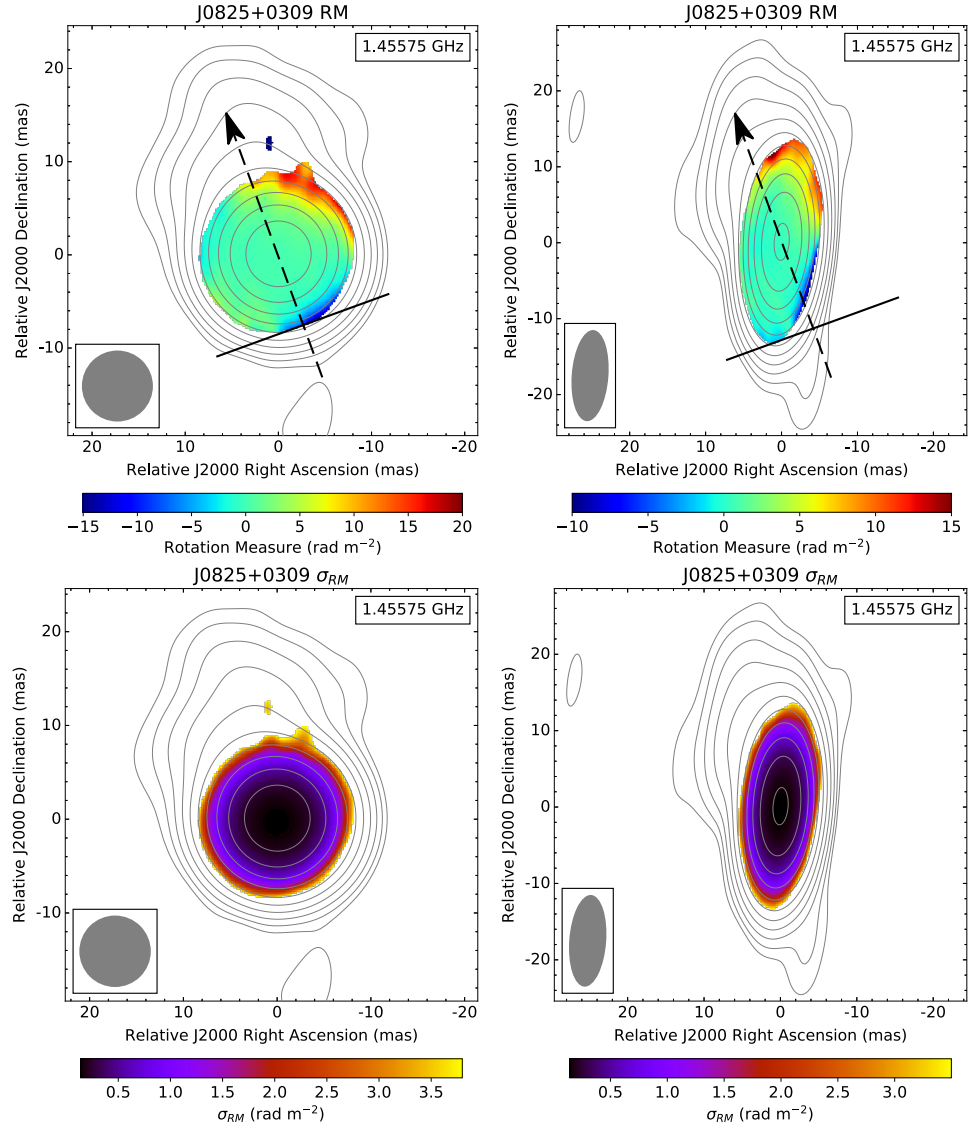


Figure 3.38: The top two panels depict the rotation measure maps for J0825+0309 convolved with the circular (left) and elliptical (right) 1.45 GHz restoring beams. The middle two panels show the corresponding error maps.

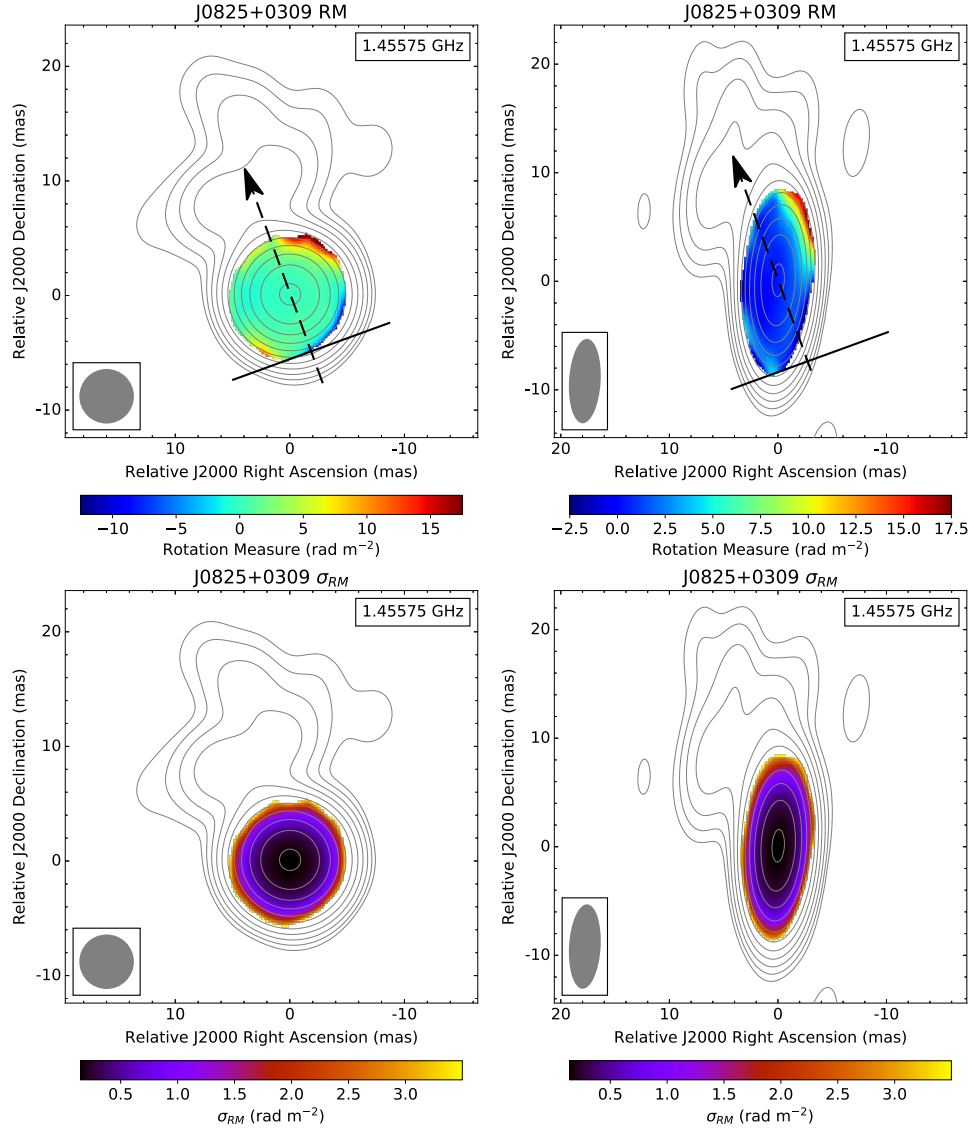


Figure 3.39: The top two panels depict the rotation measure maps for J0825+0309 convolved with the circular (left) and elliptical (right) 2.2 GHz restoring beams. The bottom two panels show the corresponding error maps.

3.2.9 J0854+2006

J0854+2006 (common name OJ 287) has a redshift of $z = 0.306$ (Stickel & Fried 1989). At both optical and radio wavelengths, it is violently variable, in both intensity and polarisation.

The 5 GHz intensity maps shown in Figure 3.40, as well as the 15 GHz and 23 GHz MOJAVE maps, show that it is initially travelling west at an angle of $\theta = -105^\circ$. The spectral index map is as expected for a partially optically thick core and optically thin jet, and is consistent with the jet direction visible in the 5 GHz images.

The 5 GHz RM_{Gal} corrected EVPAs shown in Figure 3.41 show polarisation angles perpendicular to the jet outside the core region, consistent with a longitudinal field. There are possible signs of this longitudinal field in the jet of the MOJAVE 15 GHz maps which, over time, have similar alignment beyond 2 mas west. Again, this is supported by a $\lambda = 3.6$ cm study by Gabuzda & Cawthorne (1996) which noticed little correlation between jet and polarisation angle in the core but found a suggestion of a longitudinal field outside it which makes this suggestion plausible. At 1.45 GHz, little structure can be discerned from outside the core. The χ_0 maps, which show polarisation angles close to 0° are similar to the χ_0 map by Pushkarev et al. (2012). Knowing that at much smaller scales (see the 43 GHz MOJAVE map) the jet is at a position angle $\theta \approx -90^\circ$, this raises the possibility that what we are seeing is another longitudinal field component.

The fractional polarisation maps in Figure 3.42 show the polarisation to be lowest in the core, mostly with $m \leq 5\%$. For the 1.45 GHz maps, due to the limited resolution of the large restoring beam, it cannot be verified if the increase in fractional polarisation at the edges is spurious or real.

A possible transverse RM gradient can be seen in Figure 3.43 near the end of the jet. The significance of this gradient is dependent on a small number of edge pixels. The RM maps convolved with the 2.2 GHz beam are shown in Figure 3.44. The 2.2 GHz beam RM maps show the same RM structure and confirm that the transverse RM gradients are not uniform, arising from a thin band of edge pixels. In addition, the structure of the significance plots has become different. All this indicates that this apparent gradient is unreliable. In another study, a roughly 3σ RM gradient in the core was identified using 16–22 cm data by Motter & Gabuzda (2017) in the core region. However, the significance is reduced below 2σ when convolved with a circular beam leaving the overall result tentative. It is worth noting, that the direction of this gradient is the same as that identified here, albeit located further down the jet. The polarisation angle structure described by Motter & Gabuzda (2017) is also roughly consistent with a longitudinal magnetic field.

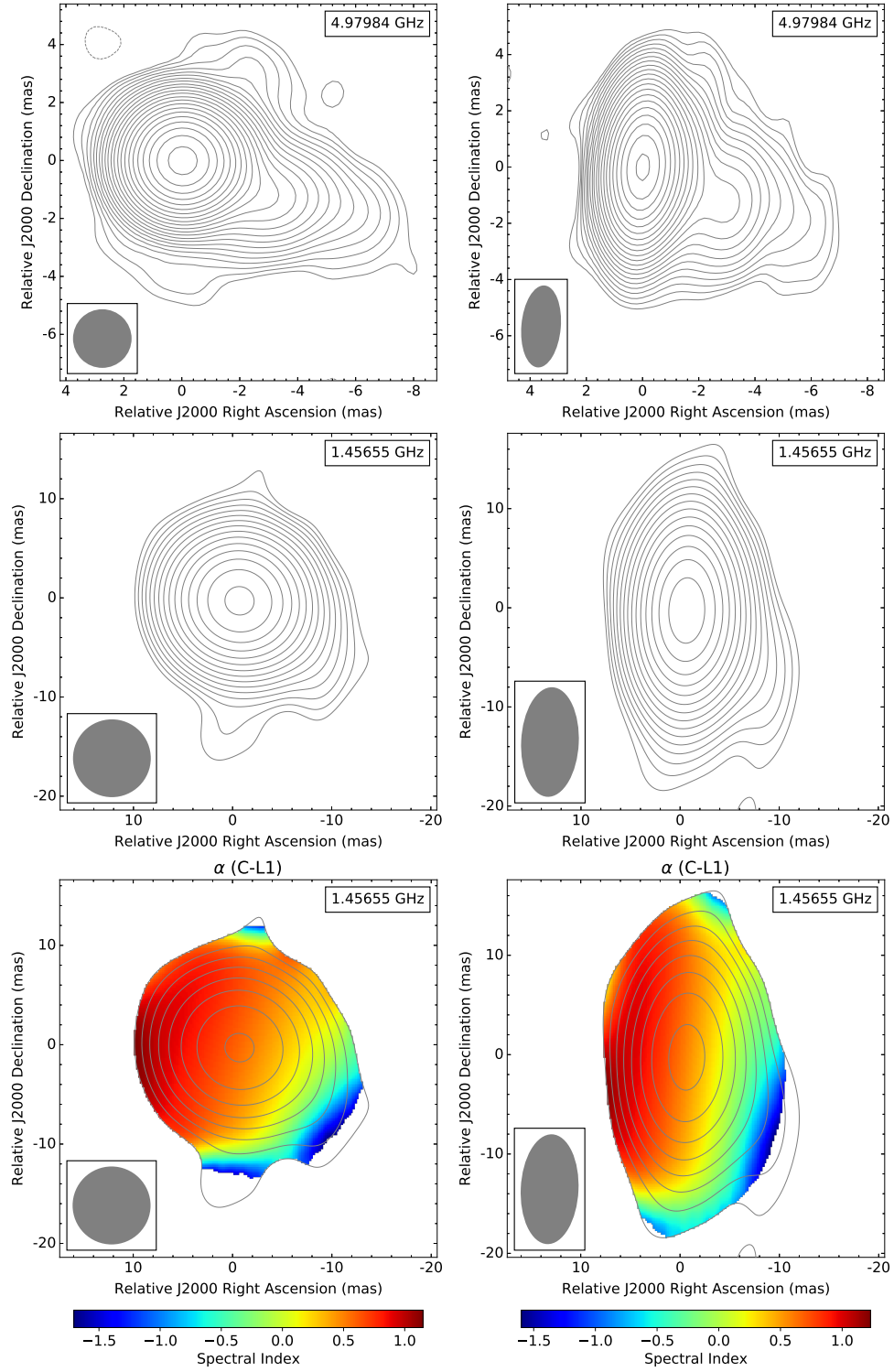


Figure 3.40: The top two panels depict the 5 GHz intensity maps for J0854+2006 convolved with the circular (left) and elliptical (right) 5 GHz beam. The middle two panels show the same for the 1.45 GHz intensity maps convolved with the 1.45 GHz beam. The bottom two panels show the C-L1 spectral index maps for J0854+2006 convolved with the 1.45 GHz beams. Intensity contours for the panels in the first two rows increase in factors of $\sqrt{2}$ and in the bottom row by factors of 2.

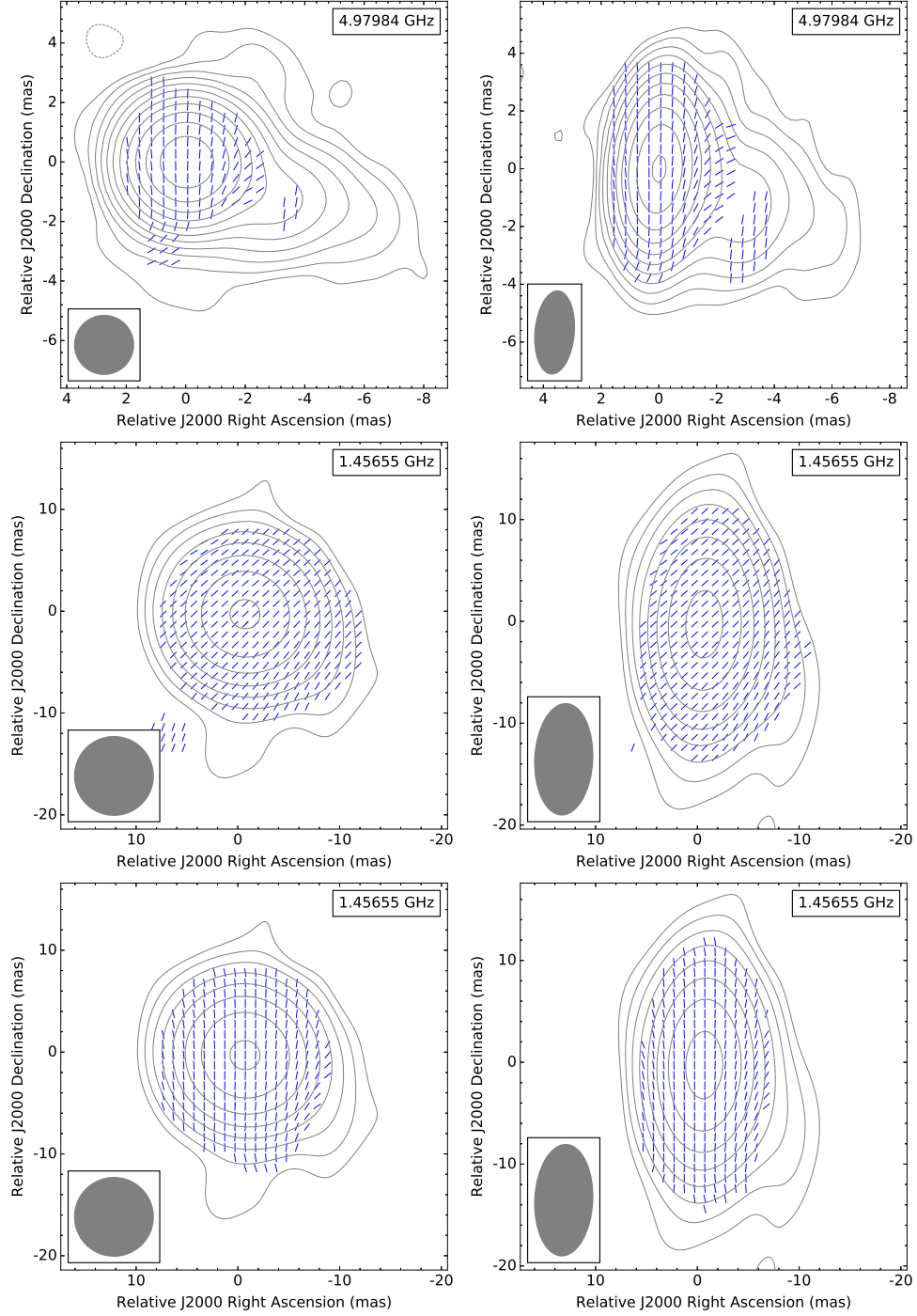


Figure 3.41: The top two panels depict the 5 GHz polarisation angle maps for J0854+2006 corrected for only the Galactic RM convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz polarisation angle maps corrected for only the Galactic RM convolved with the 1.45 GHz beam. The bottom two panels show the 1.45 GHz χ_0 maps convolved with the 1.45 GHz beams. The polarisation intensity cutoffs for the top four panels are 5 mJy/beam (5 GHz circular beam), 5 mJy/beam (5 GHz elliptical beam), 2.5 mJy/beam (1.45 GHz circular beam) and 2.75 mJy/beam (1.45 GHz elliptical beam).

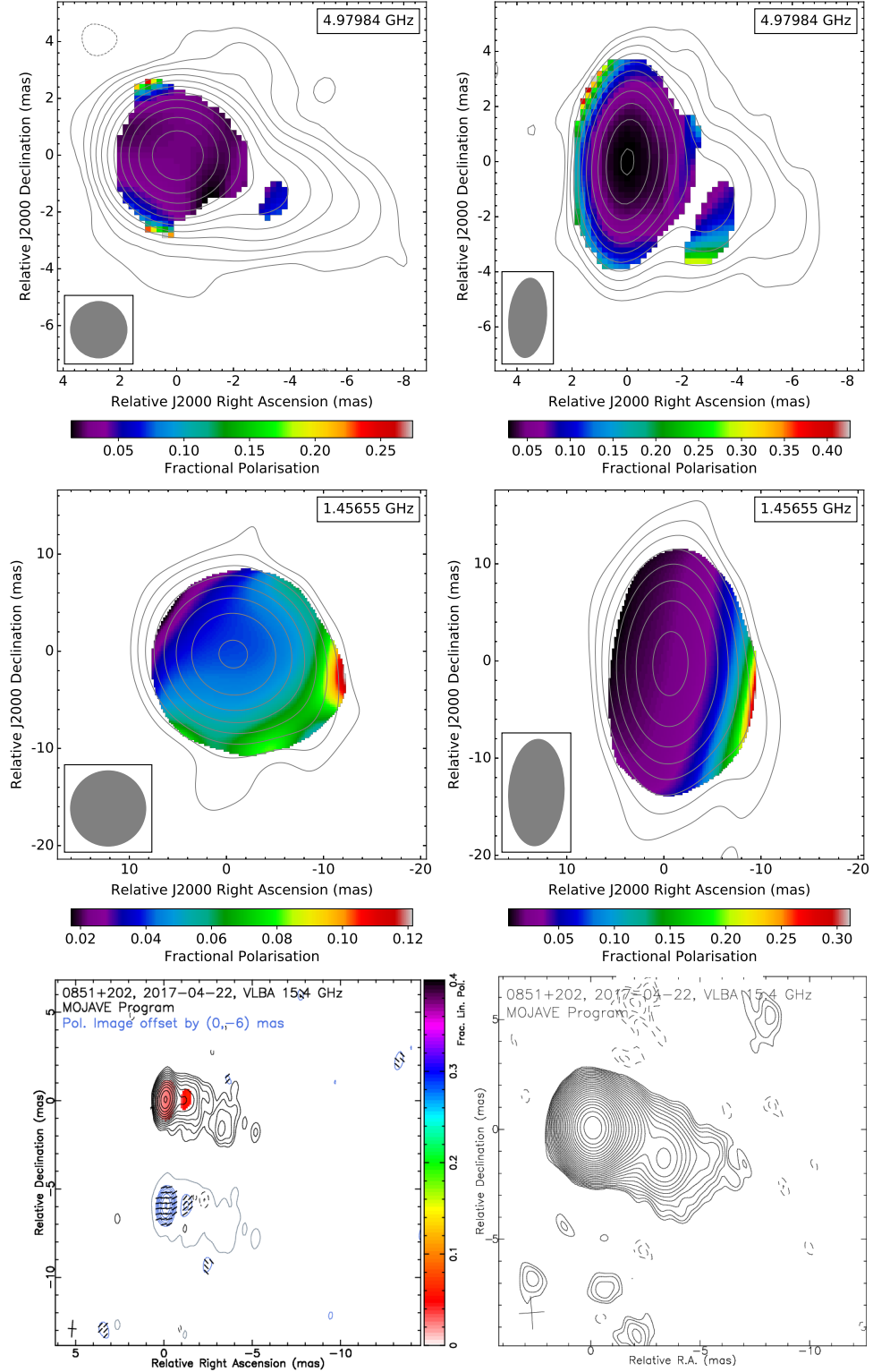


Figure 3.42: The top two panels show the 5 GHz fractional polarisation maps for J0854+2006 convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz fractional polarisation maps convolved with the 1.45 GHz beam. Polarisation intensity cutoffs are the same as in Figure 3.41. The bottom two panels show the 15 GHz MOJAVE polarisation and fractional polarisation (left) and tapered intensity (right) maps from 22/04/2017.

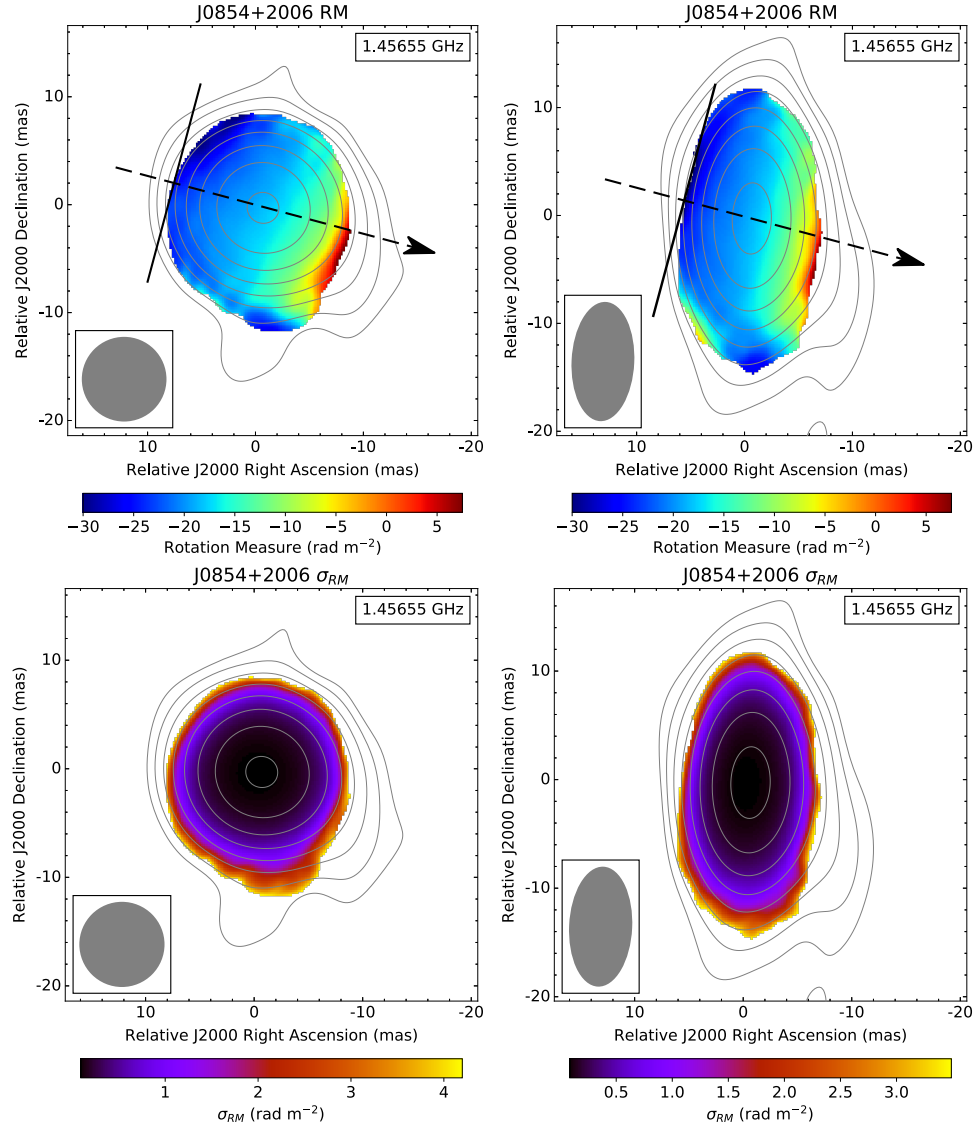


Figure 3.43: The top two panels depict the rotation measure maps for J0854+2006 convolved with the circular (left) and elliptical (right) 1.45 GHz restoring beams. The bottom two panels show the corresponding error maps.

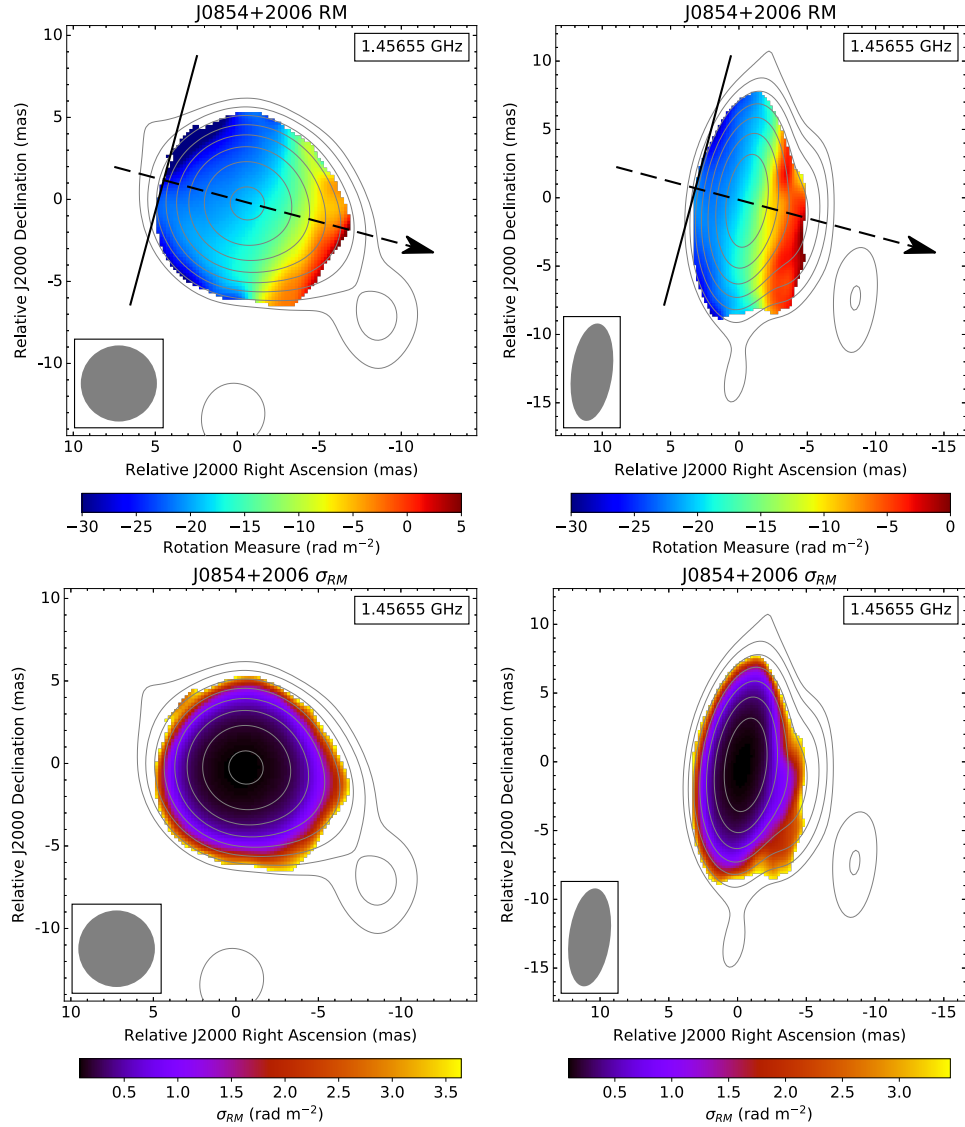


Figure 3.44: The top two panels depict the rotation measure maps for J0854+2006 convolved with the circular (left) and elliptical (right) 2.2 GHz restoring beams. The bottom two panels show the corresponding error maps.

3.2.10 J0958+6533

J0958+6533 has a redshift of $z = 0.3694$ (González et al. 2021). As can be seen in the 5 GHz intensity maps of Figure 3.45, as well as smaller-scale studies such as the 15 GHz MOJAVE observations, the jet of J0958+6533 initially goes in a north-westerly direction before experiencing multiple bends at a relative right ascension of approximately -2 , -4 , and -10 mas. Throughout this section, the jet is at $\theta \approx -90^\circ$. After bending, as can be seen in the 1.45 GHz maps, it finally travels at $\theta \approx -70^\circ$ before diffusing. The spectral index decreases monotonically with distance from the

core as expected. The core-jet gradient in the spectral-index distribution is consistent with the direction of the inner jet visible in the 5 GHz intensity map.

The polarisation angles at 5 GHz, in Figure 3.46 show evidence of a being aligned with the jet near the end of the jet, consistent with a longitudinal magnetic field in this region. Knowing the small-scale jet direction, this is also seen in 1.45 GHz RM_{Gal} corrected EVPAs, and the χ_0 maps. The orientation of the magnetic field relative to the jet direction in the core region and inner jet is not obvious.

The fractional polarisation shown in Figure 3.47 shows low polarisation in the core, ranges from 0 to 10%. In both the 5 GHz and 1.45 GHz maps the intensity of polarisation increases near regions where the jet bends where the magnetic field is more ordered on one side. This may be associated with a helical field or be due to interaction with an ambient medium.

A clear rotation measure gradient was identified perpendicular to a line at angle $\theta \approx -60^\circ$ at small scales (less than 5 mas west) in O’Sullivan & Gabuzda (2009) and well as in Kudryavtseva et al. (2010). This is before the jet bends. Another 16–22 cm study by Hallahan & Gabuzda (2008) show a possible gradient further out at 15 mas west, which will be re-examined in Chapter 4.

Guided by the structure in the 5 GHz map and the direction of the core-jet gradient in the spectral-index map, I took the initial jet direction to be to the northwest, along the direction shown in the top panel of Figure 3.48, after which the jet direction was taken to be roughly horizontal. The statistical significance plots in Figure 3.49 were obtained by taking RM slices perpendicular to these jet directions. The rotation measure maps in Figure 3.48 show a very distinct transverse RM gradient throughout the core and inner jet region, in the same direction as the gradient found by O’Sullivan & Gabuzda (2009). The apparent reversal, seen only in the elliptical beam map is likely spurious. Realistically the jet is bending at smaller scales and a strong analog of the RM gradient identified by O’Sullivan & Gabuzda (2009) may be seen from a relative right ascension of 2 to 6 mas in the results presented here.

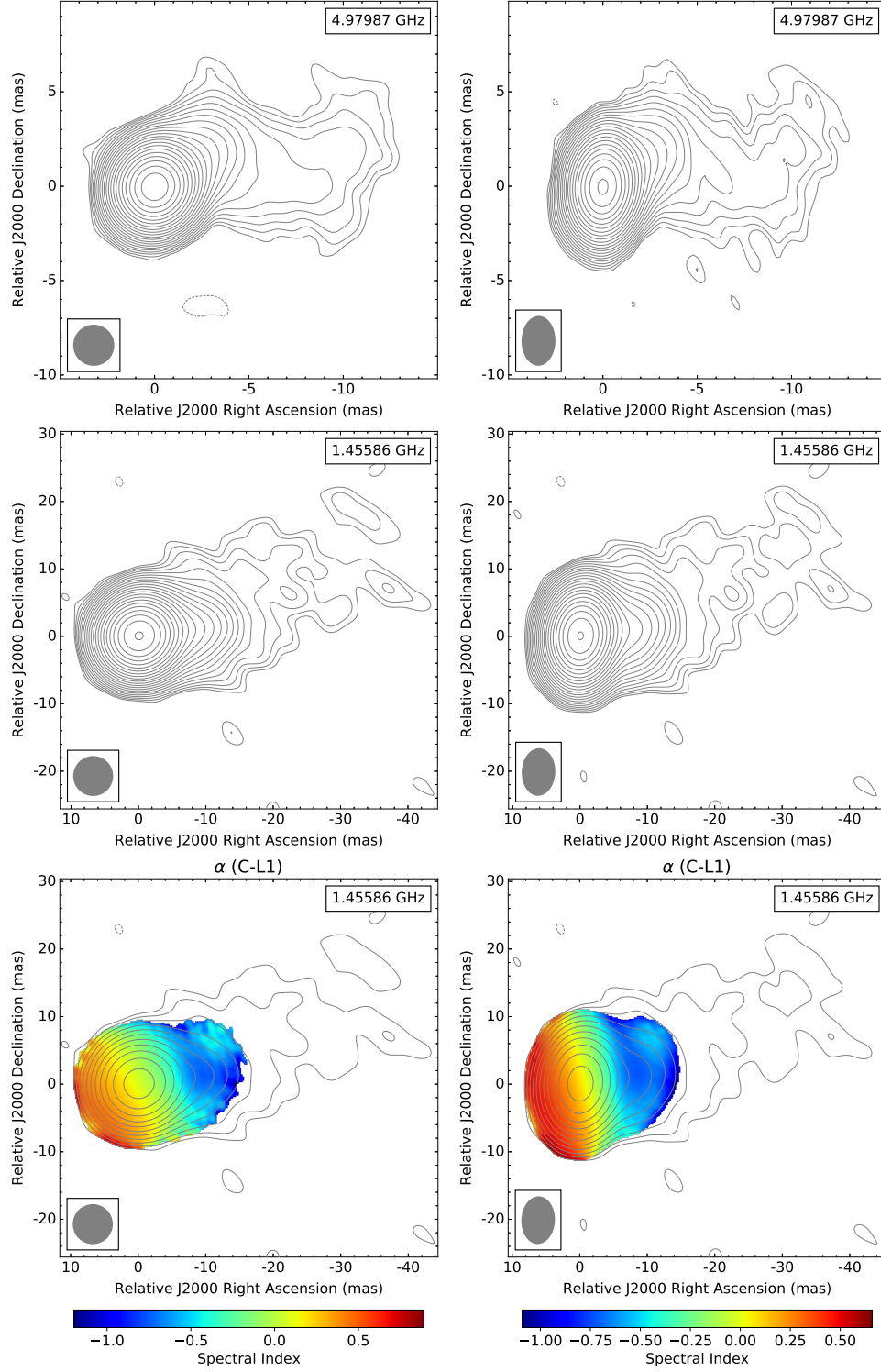


Figure 3.45: The top two panels depict the 5 GHz intensity maps for J0958+6533 convolved with the circular (left) and elliptical (right) 5 GHz beam. The middle two panels show the same for the 1.45 GHz intensity maps convolved with the 1.45 GHz beam. The bottom two panels show the C-L1 spectral index maps for J0958+6533 convolved with the 1.45 GHz beams. Intensity contours for the panels in the first two rows increase in factors of $\sqrt{2}$ and in the bottom row by factors of 2.

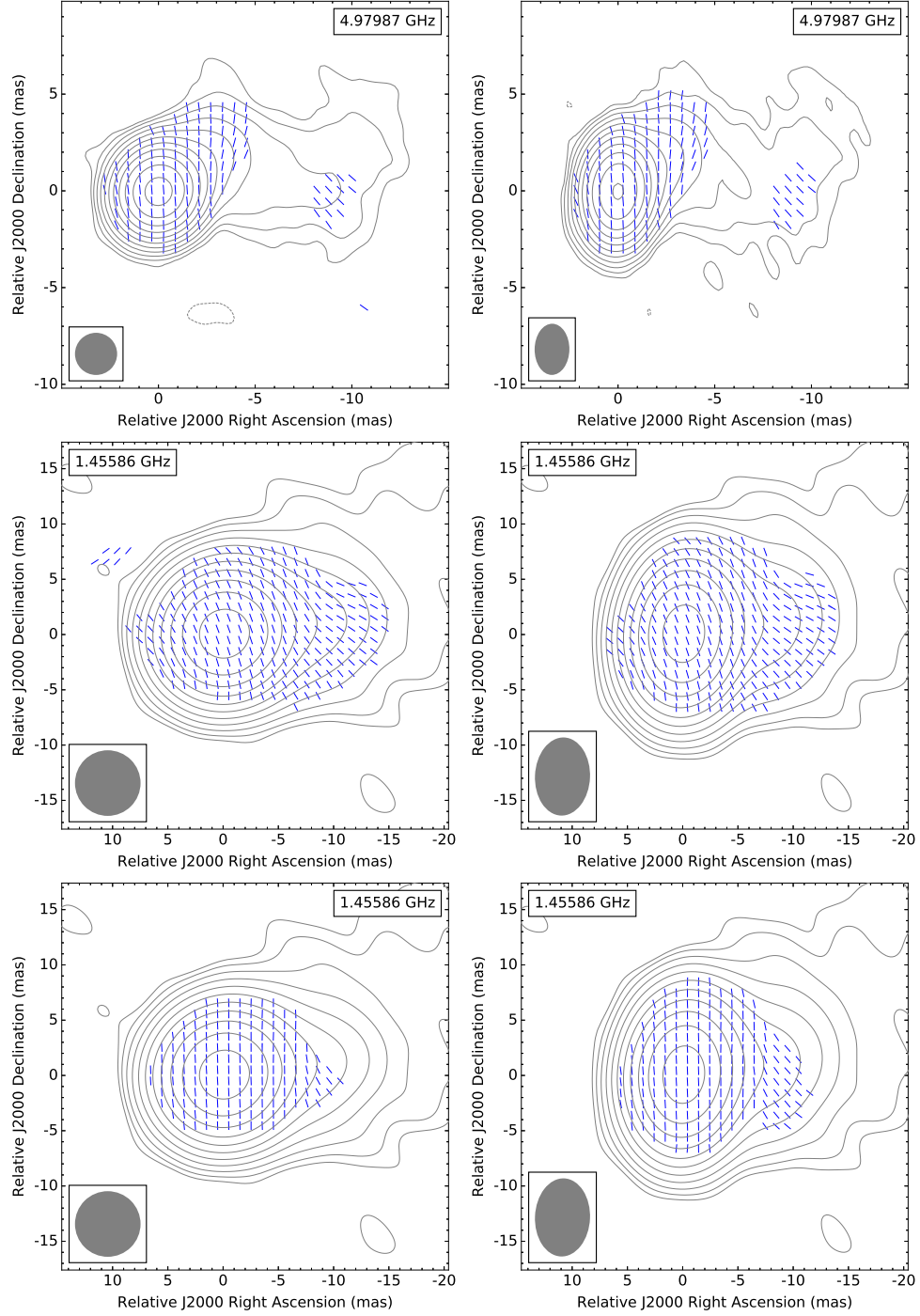


Figure 3.46: The top two panels depict the 5 GHz polarisation angle maps for J0958+6533 corrected for only the Galactic RM convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz polarisation angle maps corrected for only the Galactic RM convolved with the 1.45 GHz beam. The bottom two panels show the 1.45 GHz χ_0 maps convolved with the 1.45 GHz beams. The polarisation intensity cutoffs for the top four panels are 0.5 mJy/beam (5 GHz circular beam), 0.5 mJy/beam (5 GHz elliptical beam), 0.7 mJy/beam (1.45 GHz circular beam) and 0.7 mJy/beam (1.45 GHz elliptical beam).

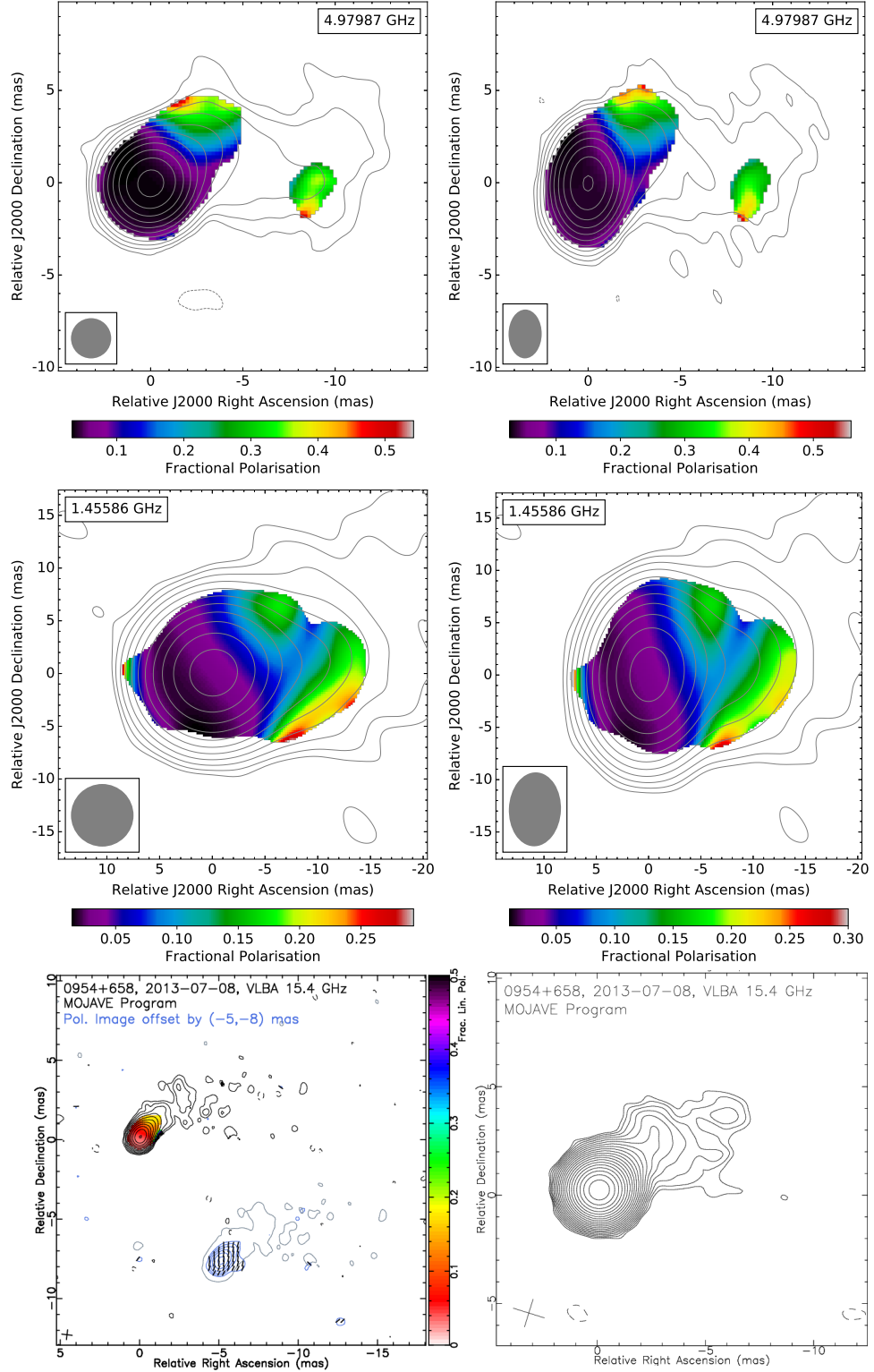


Figure 3.47: The top two panels show the 5 GHz fractional polarisation maps for J0958+6533 convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz fractional polarisation maps convolved with the 1.45 GHz beam. Polarisation intensity cutoffs are the same as in Figure 3.46. The bottom two panels show the 15 GHz MOJAVE polarisation and fractional polarisation (left) and tapered intensity (right) maps from 08/07/2013.

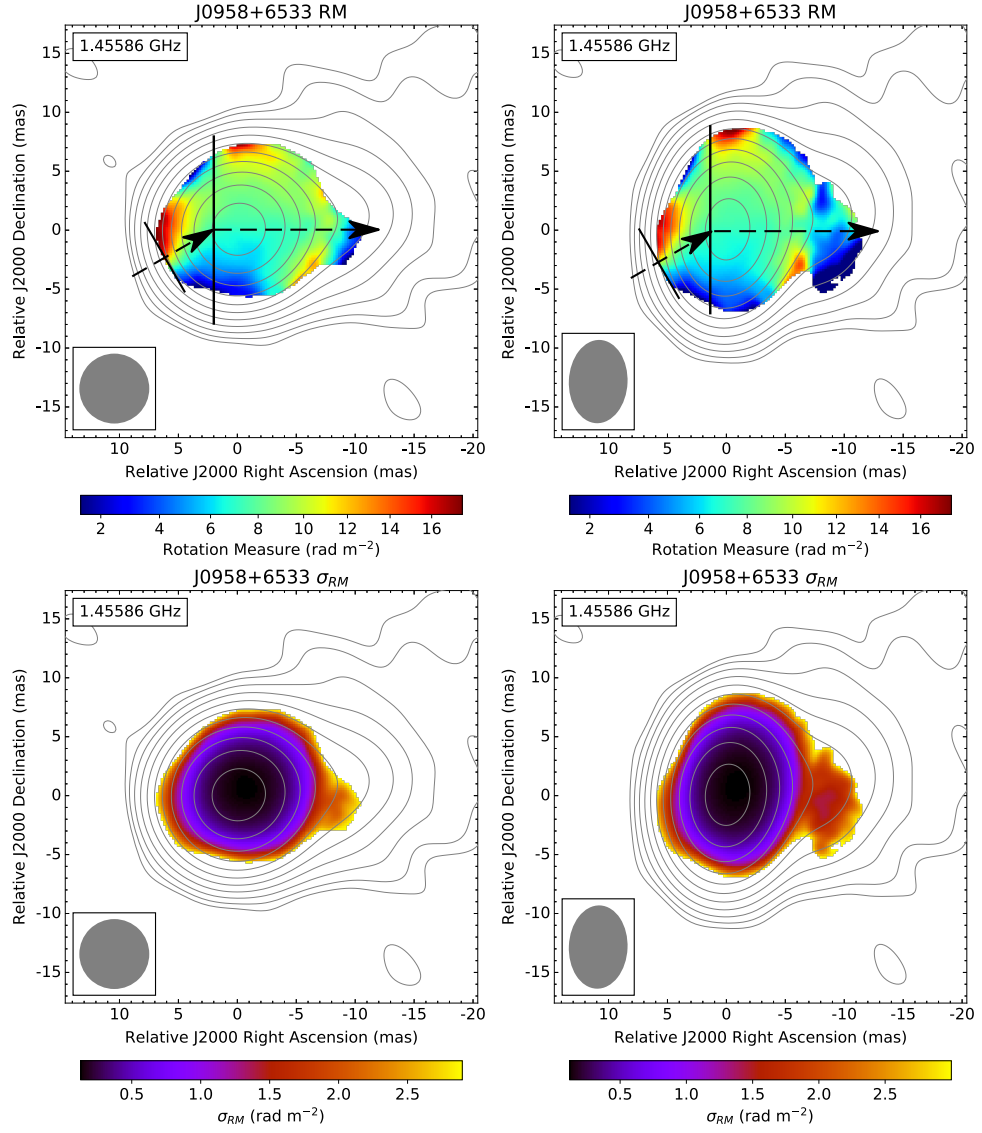


Figure 3.48: The top two panels depict the rotation measure maps for J0958+6533 convolved with the circular (left) and elliptical (right) 1.45 GHz restoring beams. The bottom two panels show the corresponding error maps. Plots of the estimated significances of the difference of the RM values on either side of the jet are shown in Figure 3.49.

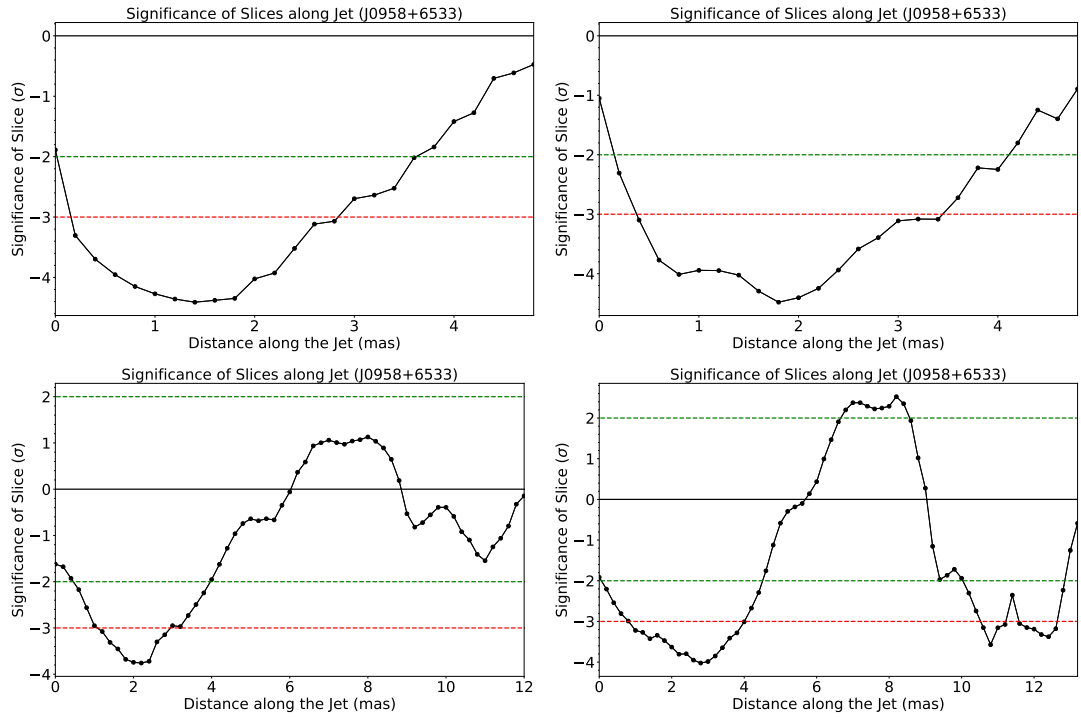


Figure 3.49: These panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrows shown in the top two panels of Figure 3.48. The top two panels of this figure are the core region from a relative right ascension of 6 to 2 mas. The bottom two panels are from a relative right ascension of 2 to -10 mas.

3.2.11 J1751+0939

J1751+0939 (common name OT 081) has a redshift of $z = 0.322$ (Stickel et al. 1988). The core region is very compact and as seen in Figure 3.50, the jet travels northeast at an angle of $\theta \approx 30^\circ$ up to relative declination of 50 mas. The spectral index maps exhibit the expected behaviour for a partially optically thick core, with α decreasing with distance along the jet. The core-jet spectral-index gradient is consistent with the observed jet direction.

The polarisation angles in Figure 3.51 show there is little appreciable polarisation in the jet. Previous studies such as Gabuzda et al. (2008), show that the dominant B field has been orthogonal to the jet, with polarisation angles aligned in the inner jet and possible hints of a spine-sheath structure. The 15 GHz MOJAVE maps, however, show polarisation structure to be quite variable. In Figure 3.51, the polarisation angles are homogeneous at about $\chi = -60^\circ$ over the entire core region consistent with a magnetic field aligned with the jet in this region.

Fractional polarisation, shown in Figure 3.52 shows m to be less than 10% for most of the core region. There is an increase towards the western edge of the core region for a few pixels but this may be spurious.

Previously a rotation measure gradient was identified in J1751+0939 in Gabuzda et al. (2008) with further analysis in Gabuzda et al. (2015) confirming that the monotonic, transverse RM gradient across the core has a significance of 5.5σ . A gradient with the same sense was visible in the 8.1–15.2 GHz RM map of Zavala & Taylor (2004). The rotation measure map shown in Figure 3.53 shows a possible gradient in the same direction, perpendicular to the jet direction. The maximum significance is 3.75σ for the circular beam map and 5.3σ for the elliptical beam. At the same time, the gradient is not very uniform across the jet, bringing its reality into doubt. The gradients detected in the earlier observations were all somewhat closer to the jet base. To help clarify this, RM maps convolved with the 2.2 GHz beam were made, the results of which are shown in Figure 3.54. Although the transverse RM gradient appears somewhat more convincing by eye in the RM map made using the circular 2.2 GHz beam, it has completely disappeared from the corresponding map made using the elliptical beam, and the structure of the two significance plots is now completely different. Overall, these results show that this apparent transverse RM gradient is not reliable.

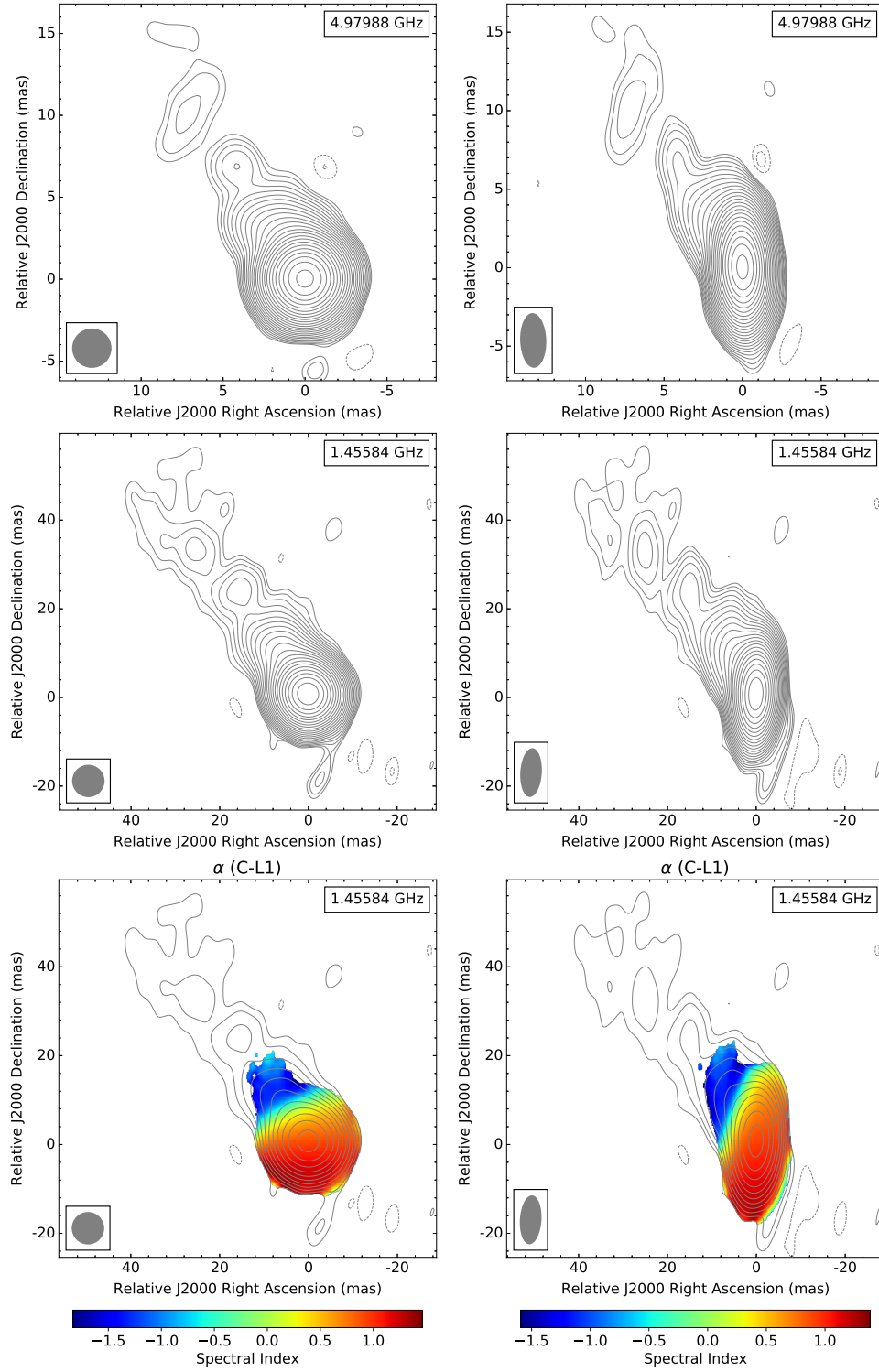


Figure 3.50: The top two panels depict the 5 GHz intensity maps for J1751+0939 convolved with the circular (left) and elliptical (right) 5 GHz beam. The middle two panels show the same for the 1.45 GHz intensity maps convolved with the 1.45 GHz beam. The bottom two panels show the C-L1 spectral index maps for J1751+0939 convolved with the 1.45 GHz beams. Intensity contours for the panels in the first two rows increase in factors of $\sqrt{2}$ and in the bottom row by factors of 2.

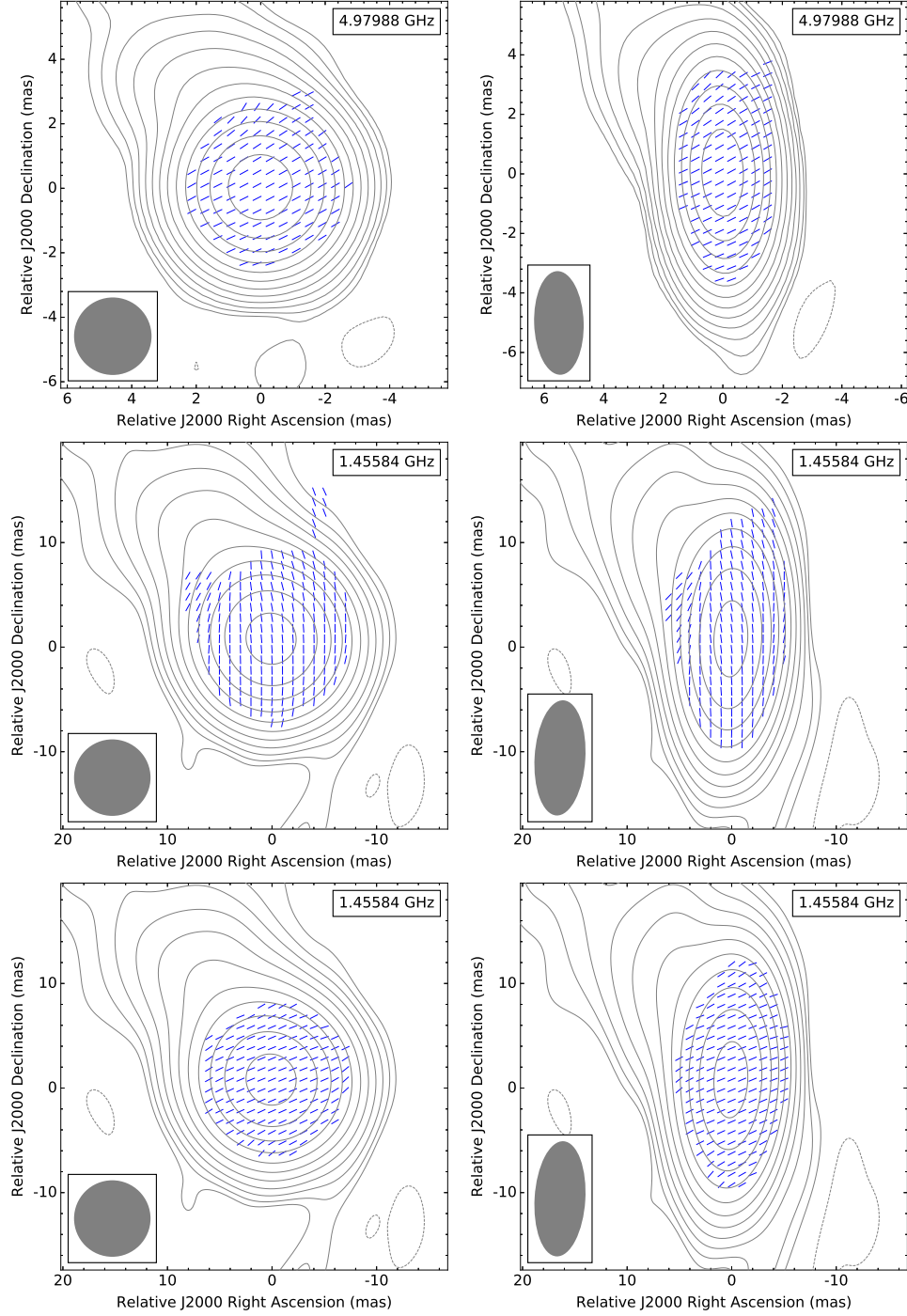


Figure 3.51: The top two panels depict the 5 GHz polarisation angle maps for J1751+0939 corrected for only the Galactic RM convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz polarisation angle maps corrected for only the Galactic RM convolved with the 1.45 GHz beam. The bottom two panels show the 1.45 GHz χ_0 maps convolved with the 1.45 GHz beams. The polarisation intensity cutoffs for the top four panels are 7.5 mJy/beam (5 GHz circular beam), 6 mJy/beam (5 GHz elliptical beam), 0.8 mJy/beam (1.45 GHz circular beam) and 1 mJy/beam (1.45 GHz elliptical beam).

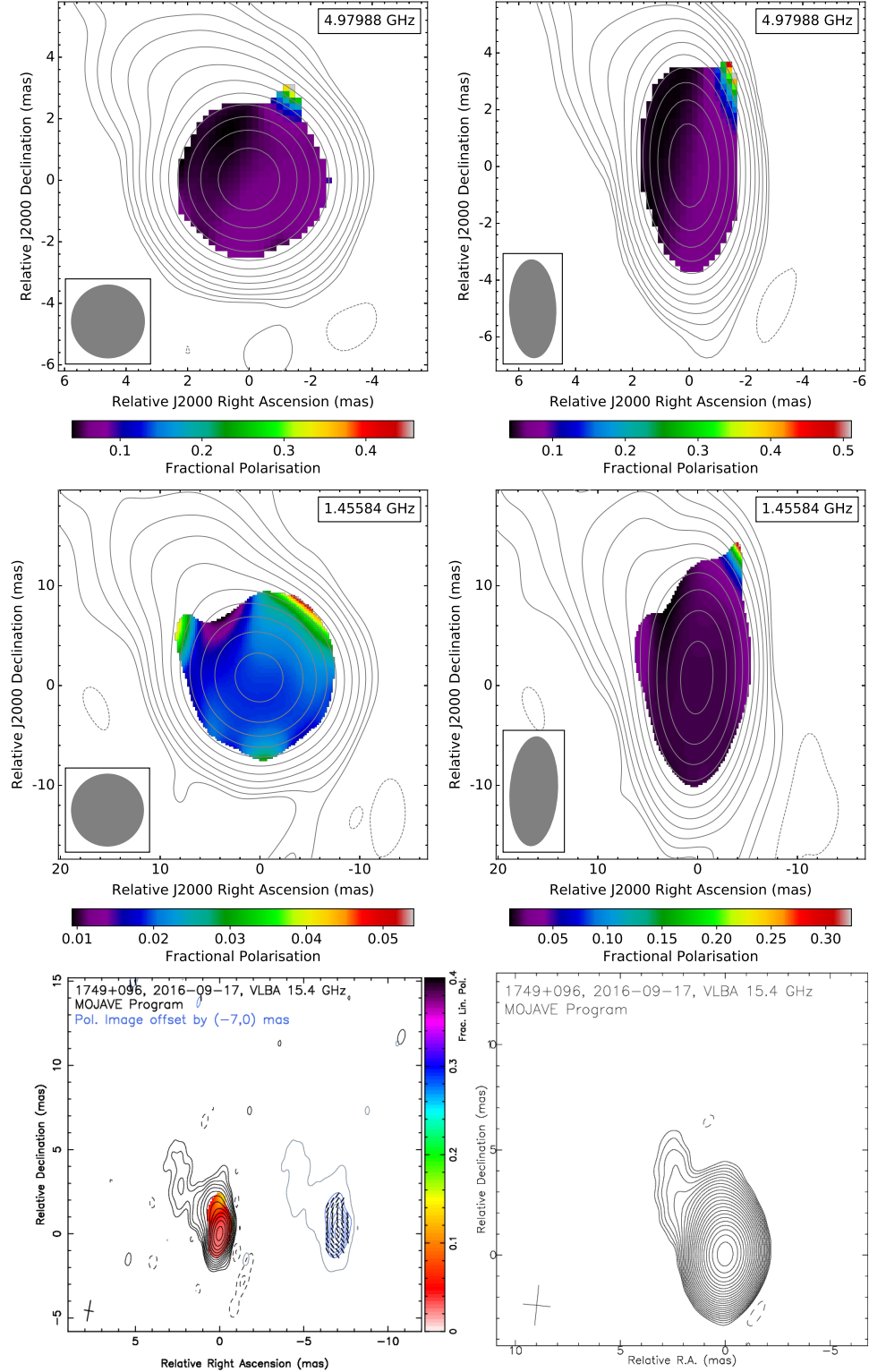


Figure 3.52: The top two panels show the 5 GHz fractional polarisation maps for J1751+0939 convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz fractional polarisation maps convolved with the 1.45 GHz beam. Polarisation intensity cutoffs are the same as in Figure 3.51. The bottom two panels show the 15 GHz MOJAVE polarisation and fractional polarisation (left) and tapered intensity (right) maps from 17/09/2016.

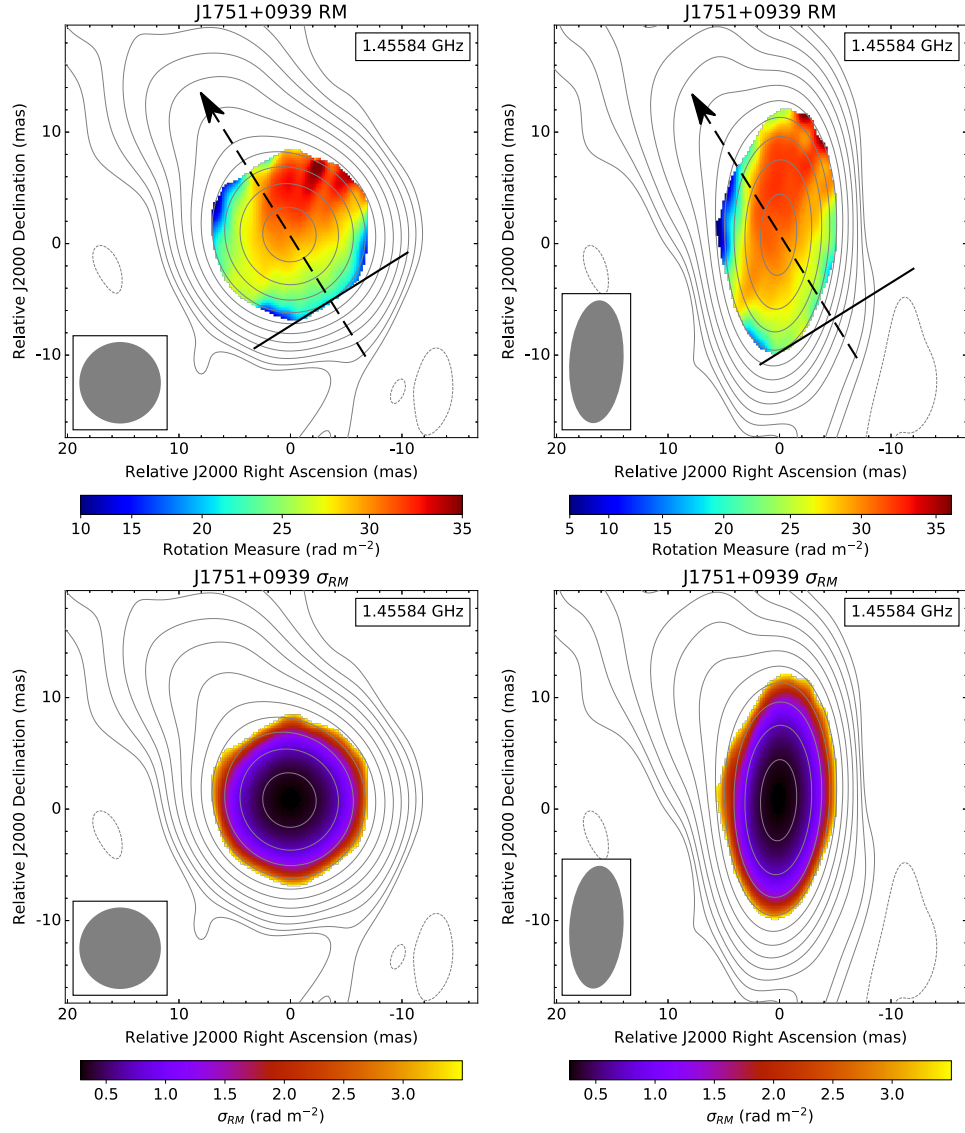


Figure 3.53: The top two panels depict the rotation measure maps for J1751+0939 convolved with the circular (left) and elliptical (right) 1.45 GHz restoring beams. The bottom two panels show the corresponding error maps.

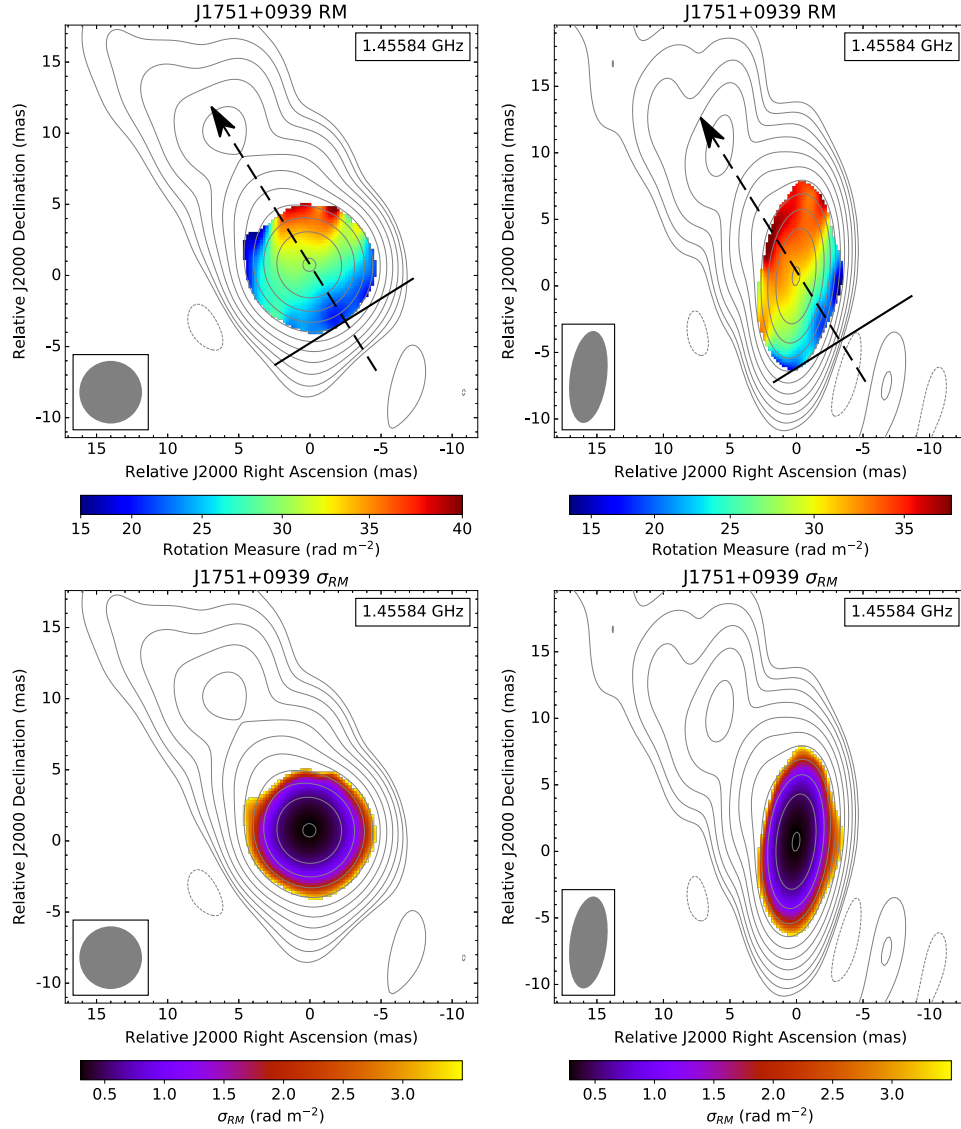


Figure 3.54: The top two panels depict the rotation measure maps for J1751+0939 convolved with the circular (left) and elliptical (right) 2.2 GHz restoring beams. The bottom two panels show the corresponding error maps.

3.2.12 J1800+7828

J1800+7828 has a redshift of $z = 0.683$ (Paiano et al. 2020). The intensity maps shown in Figure 3.55, as well as the MOJAVE 15 GHz, 23 GHz, and 43 GHz observations, show the jet initially travels west from the core at an angle close to $\theta = 90^\circ$, before changing direction towards the south at 10 mas west. Another bend occurs towards the north at about 30 mas west and the jet becomes diffuse at 1.45 GHz scales. The spectral index decreases monotonically with distance from the partially optically thick core as expected, and the core-jet gradient in the spectral-index map is

consistent with the initial emergence of the jet nearly directly toward the west.

Various studies of J1800+7828 at higher frequencies such as Gabuzda et al. (1992) and Gabuzda et al. (1994), have found that the jet of J1800+7828 consists of several distinct components, which may represent shocks travelling along the jet. Other studies suggest that J1800+7828 has a field that is orthogonal to the jet direction along its length (Gabuzda & Chernetskii 2003). This is further supported by the MOJAVE 15, 23, and 43 GHz observations, the Hovatta et al. (2012) χ_0 map, and the maps shown in Figure 3.56, which all show the parallel alignment of EVPAs with the jet. The polarisation angles remain parallel to the jet direction along its length even as it bends. An analytical approach by Cawthorne et al. (2013) noted a similarity between observed 7 mm and model polarisations that supports the view that the core structure in J1800+7828 represents a recollimation shock. However, on a larger scale, the presence of a toroidal or helical magnetic field in the jet of J1800+7828 is the more likely explanation for the observed structure, considering the uniformity of the transverse field along the jet.

The distribution of fractional polarisation in J1800+7828 is shown in Figure 3.57. The degree of polarisation is modest. Generally, there seems to be an increase in fractional polarisation towards the south side of the jet. Furthermore, in the 1.45 GHz maps, 20 mas west, there seems to be a region where the polarised intensity increases towards both sides of the jet, indicative of a possible helical field.

Numerous studies have noted Faraday rotation measure gradients in J1800+7828. Interestingly the source has shown reversals over time. Mahmud et al. (2007) discusses how the direction of the RM gradient flips between June 2000 and August 2002. Furthermore, the 2002 observation in Mahmud et al. (2007) differs in direction to another RM gradient in Zavala & Taylor (2003). Explanations provided at that time include reversal of the "pole" of the black hole facing the Earth, torsional oscillations of the jet, a "nested-helix" magnetic field structure, and alterations in the distribution of thermal electrons surrounding the jet. The nested-helix scenario is probably the simplest and the most likely. In the results presented here, assuming the jet generally stays close to $\theta = 90^\circ$ for the first 10 mas west, there also seems to be a statically significant ($\sigma > 3$) reversal at the beginning of the jet. The gradient may even flip again further out the jet, although the gradients beyond 10 mas west do not exceed 3σ and therefore are tentative.

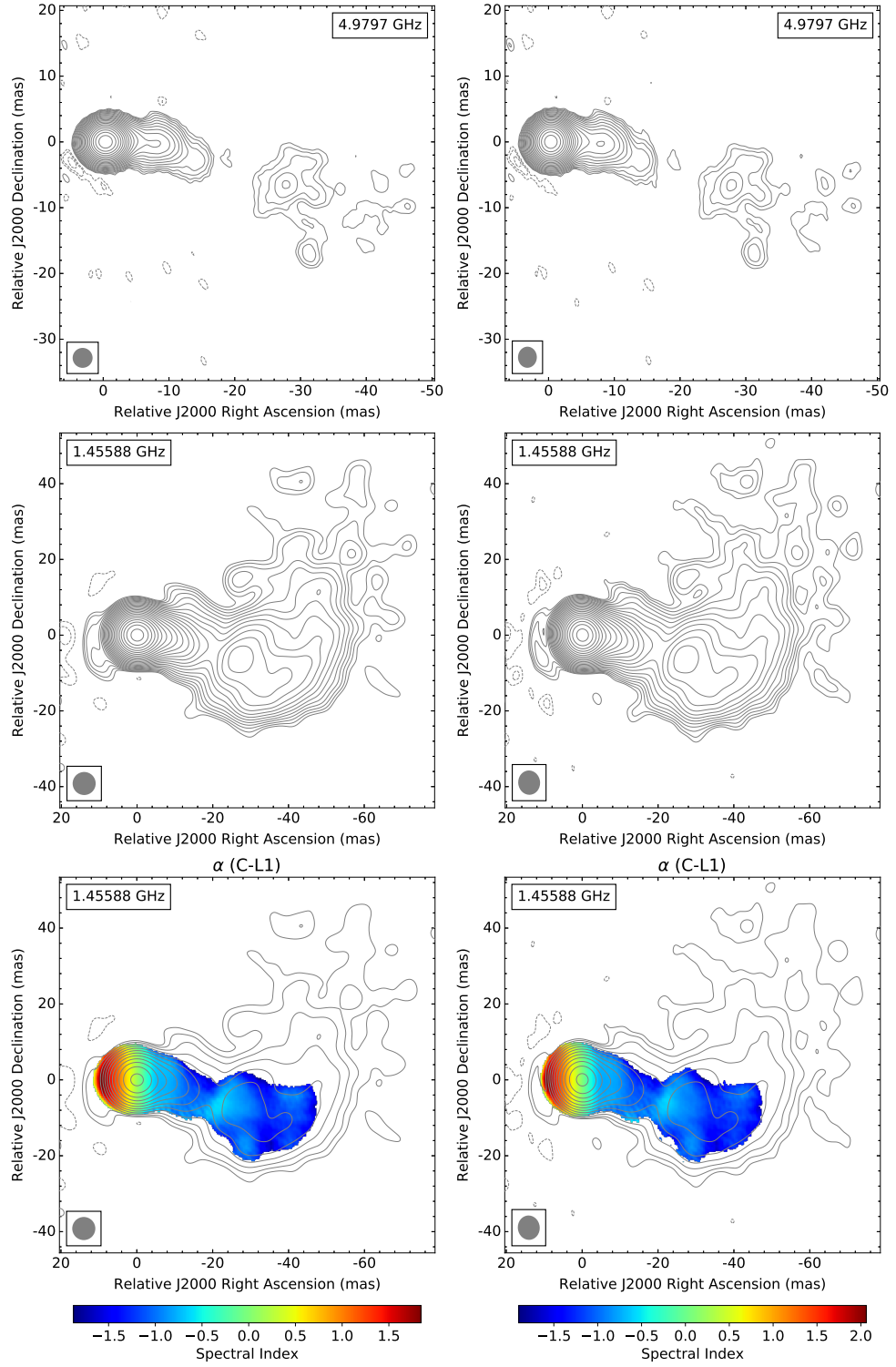


Figure 3.55: The top two panels depict the 5 GHz intensity maps for J1800+7828 convolved with the circular (left) and elliptical (right) 5 GHz beam. The middle two panels show the same for the 1.45 GHz intensity maps convolved with the 1.45 GHz beam. The bottom two panels show the C-L1 spectral index maps for J1800+7828 convolved with the 1.45 GHz beams. Intensity contours for the panels in the first two rows increase in factors of $\sqrt{2}$ and in the bottom row by factors of 2.

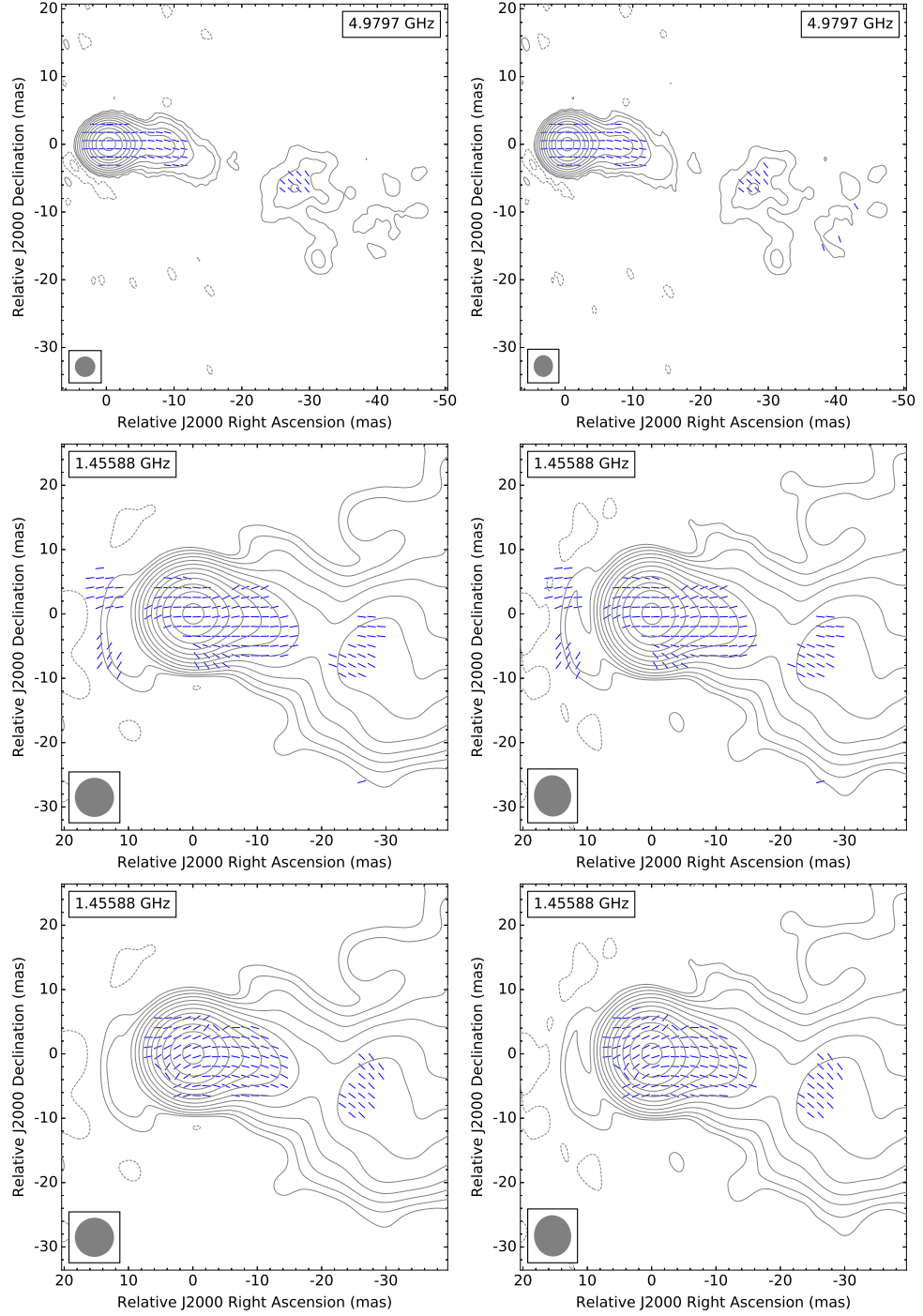


Figure 3.56: The top two panels depict the 5 GHz polarisation angle maps for J1800+7828 corrected for only the Galactic RM convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz polarisation angle maps corrected for only the Galactic RM convolved with the 1.45 GHz beam. The bottom two panels show the 1.45 GHz χ_0 maps convolved with the 1.45 GHz beams. The polarisation intensity cutoffs for the top four panels are 1.14 mJy/beam (5 GHz circular beam), 1.12 mJy/beam (5 GHz elliptical beam), 3.75 mJy/beam (1.45 GHz circular beam) and 3.75 mJy/beam (1.45 GHz elliptical beam).

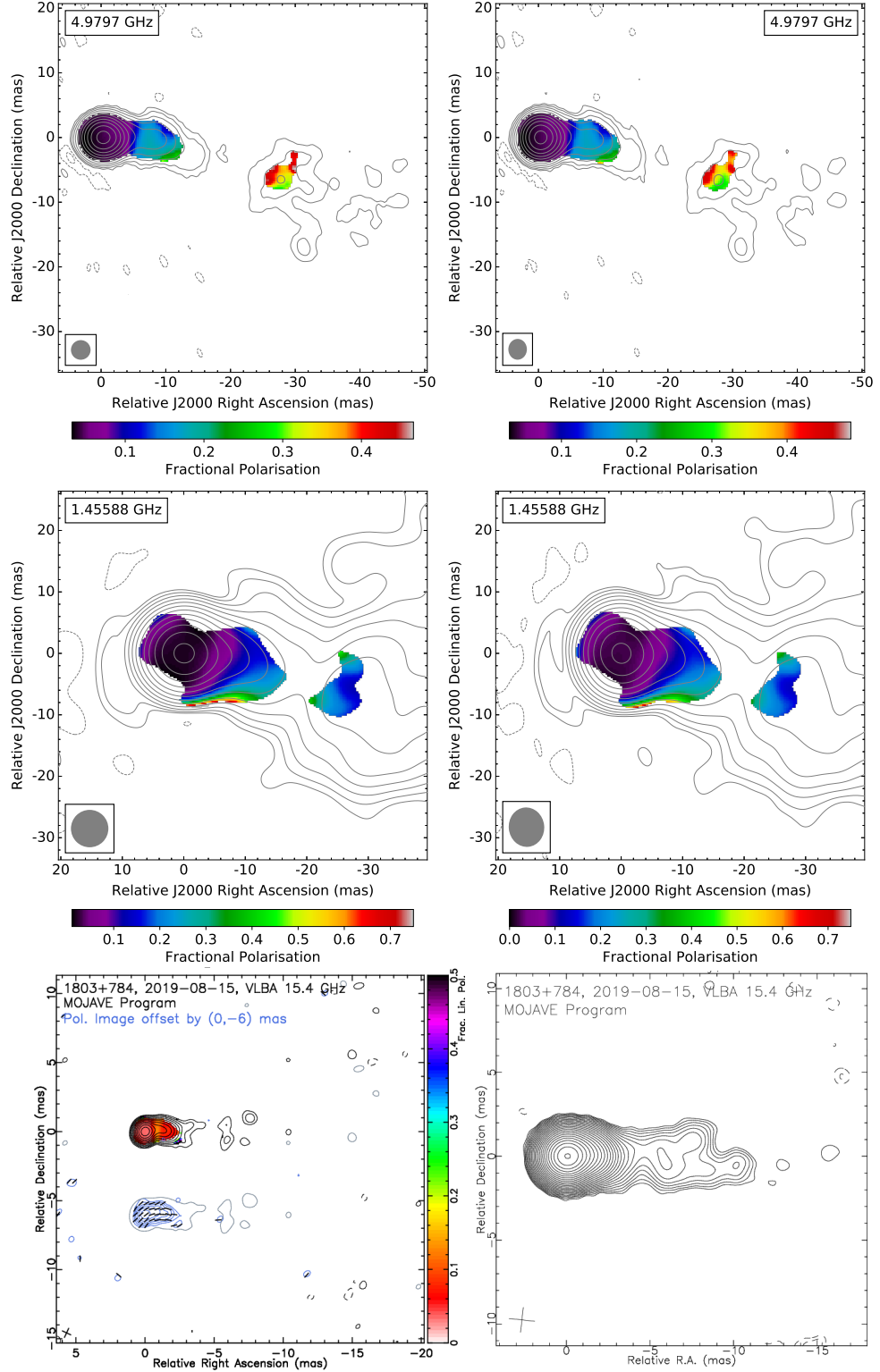


Figure 3.57: The top two panels show the 5 GHz fractional polarisation maps for J1800+7828 convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz fractional polarisation maps convolved with the 1.45 GHz beam. Polarisation intensity cutoffs are the same as in Figure 3.56. The bottom two panels show the 15 GHz MOJAVE polarisation and fractional polarisation (left) and tapered intensity (right) maps from 15/08/2019.

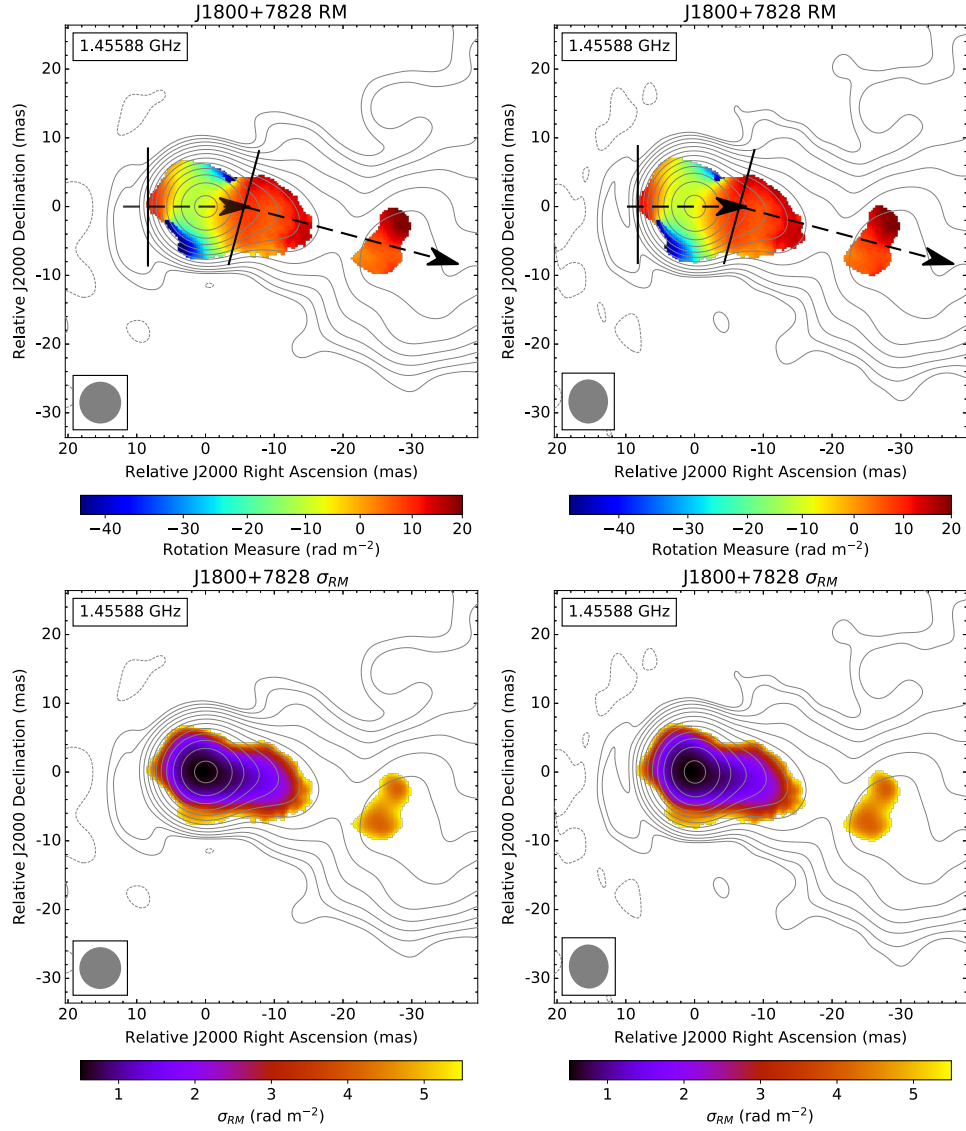


Figure 3.58: The top two panels depict the rotation measure maps for J1800+7828 convolved with the circular (left) and elliptical (right) 1.45 GHz restoring beams. The bottom two panels show the corresponding error maps. Due to high noise in the L2 band data, these panels were made only using polarisation data from the C, S, and L1 bands. Plots of the estimated significances of the difference of the RM values on either side of the jet are shown in Figure 3.59.

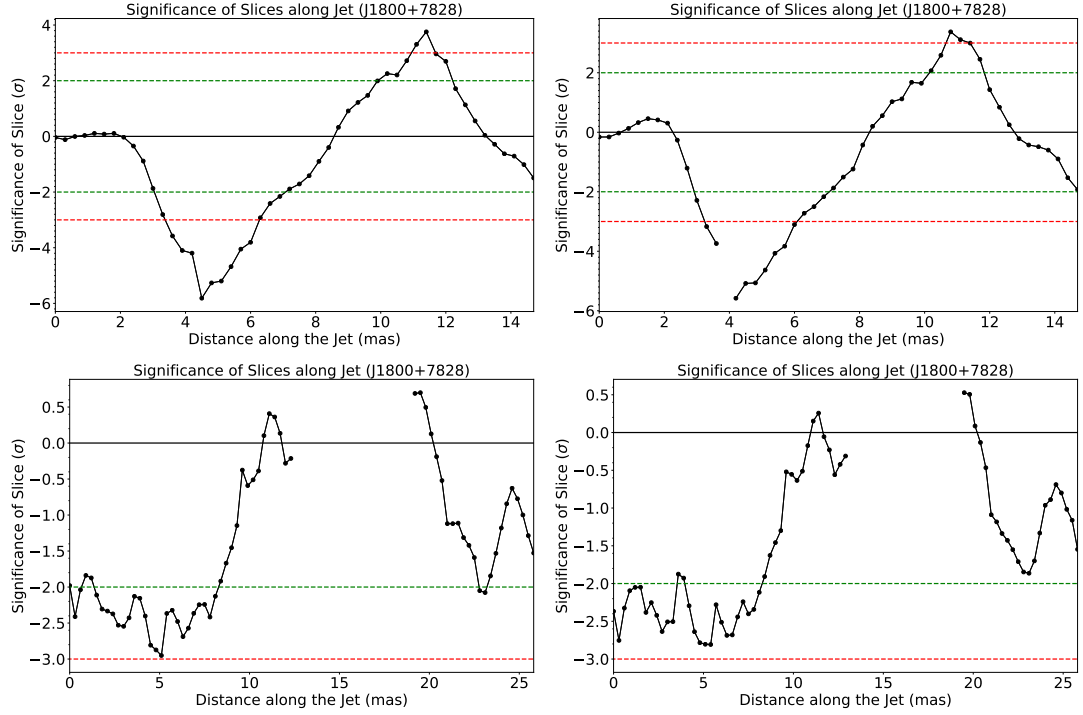


Figure 3.59: These panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrows shown in the top two panels of Figure 3.58. The top two panels of this figure are the core region and inner jet. The bottom two panels are the jet after bending, from a relative right ascension of -8 to -30 mas, beginning where the top panel ends. At the point of intersection between the two dotted arrows, the calculated significance is in the range of -2σ .

In addition, increases in RM seem to correspond to a similar rise in fractional polarisation in the same part of the jet. This implies that the Faraday rotation observed is associated with the material in the vicinity of the jet, rather than due to material in the interstellar medium. This also suggests a connection between the RM gradients, fractional polarisation distribution, and local magnetic field.

3.2.13 J1806+6949

J1806+6949 (common name 3C 371) has a redshift of $z = 0.051$ (de Grijp et al. 1992). In the 15 GHz, 23 GHz, and 43 GHz MOJAVE maps, as well as the intensity maps in Figure 3.60, the jet follows a straight line at an angle of $\theta = -100^\circ$. In the 1.45 GHz intensity maps, traces of the jet are noticeable at a relative right ascension of over -400 mas. The core-jet gradient in the spectral index map is consistent with the observed direction of the jet.

The 15 GHz MOJAVE polarisation maps remain stable over time and a RM_{Gal} corrected polarisation study at $\lambda = 6$ cm by Cawthorne et al. (1993) show polarisation angles in the core to be almost orthogonal to the jet implying a longitudinal field locally. This is consistent with the 5 GHz RM_{Gal} corrected core EVPAs shown in Figure 3.61. However, in the jet (greater than 10 mas west), EVPAs are aligned with the jet direction. Due to the patchy nature of the 1.45 GHz polarisation, little can be said about the corresponding 1.45 GHz maps. However, the χ_0 maps (bottom panels) show an indication of the parallel alignment in the inner jet, just like the 5 GHz maps, overall indicating an orthogonal magnetic field greater than 10 mas west.

The polarised intensity of J1806+6949 is modest, with fractional polarisation shown in Figure 3.62 remaining below 10% in the core. This fraction increases above 50% outside the core, especially towards the southern side of the jet. This is possibly an indication of a helical magnetic field.

The rotation measure maps shown Figure 3.63 show a "checkerboard" pattern with two regions with an RM gradient, the gradient direction undergoing a reversal along the distribution. The first has a significance of about 3σ while the latter exceeding 9σ . As mentioned earlier in the discussion of J0721+7120 and J1800+7828 the most likely explanation for such an RM-gradient reversal is believed to be a "nested-helix" magnetic field structure. A rotation measure gradient originally detected by Gabuzda et al. (2004) at 2–6 cm and confirmed to be monotonic and have a significance of 3.5σ in Gabuzda et al. (2015) coincides with the direction of the first gradient but was located slightly further down the jet.

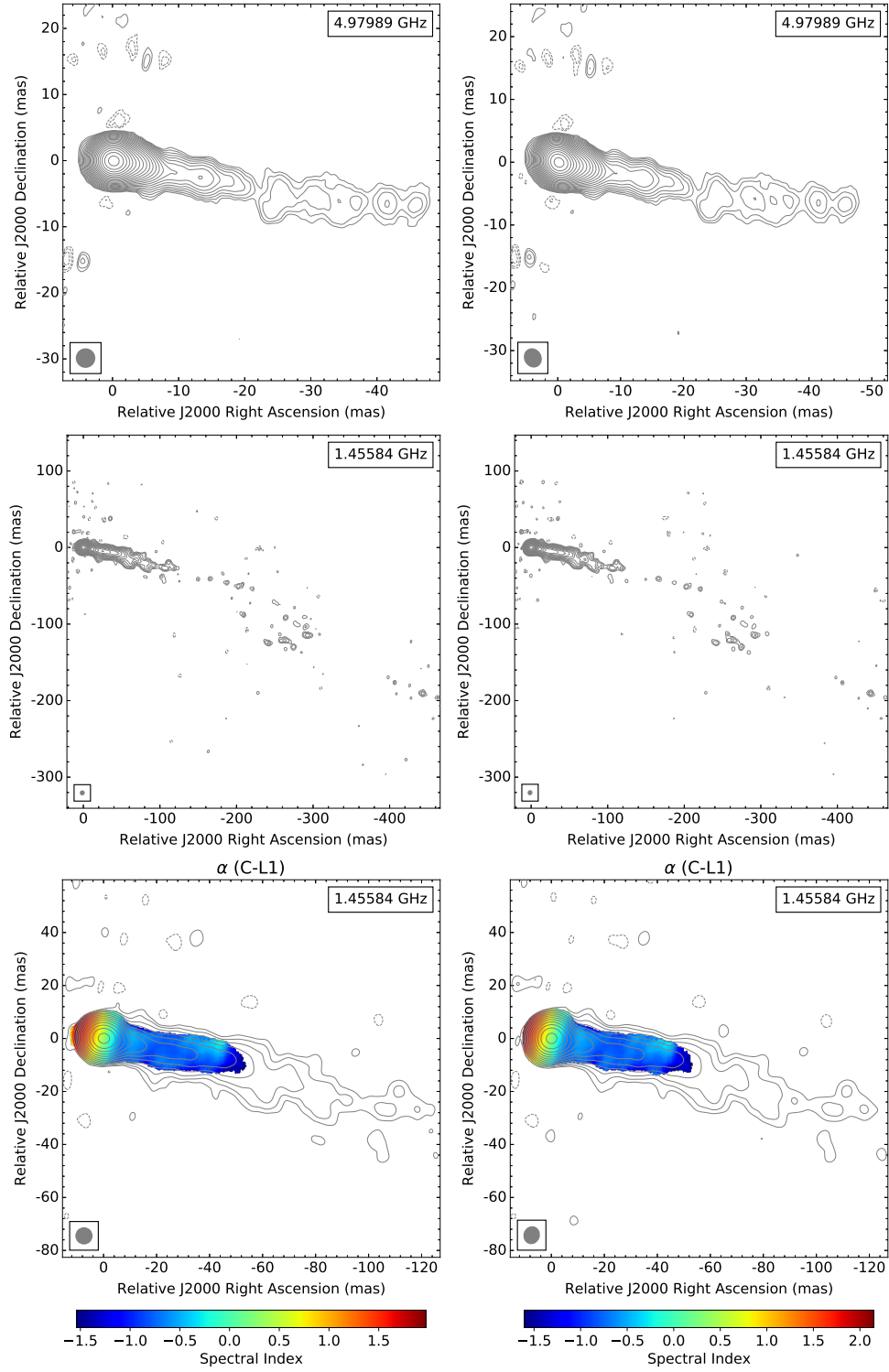


Figure 3.60: The top two panels depict the 5 GHz intensity maps for J1806+6949 convolved with the circular (left) and elliptical (right) 5 GHz beam. The middle two panels show the same for the 1.45 GHz intensity maps convolved with the 1.45 GHz beam. The bottom two panels show the C-L1 spectral index maps for J1806+6949 convolved with the 1.45 GHz beams. Intensity contours for the panels in the first two rows increase in factors of $\sqrt{2}$ and in the bottom row by factors of 2.

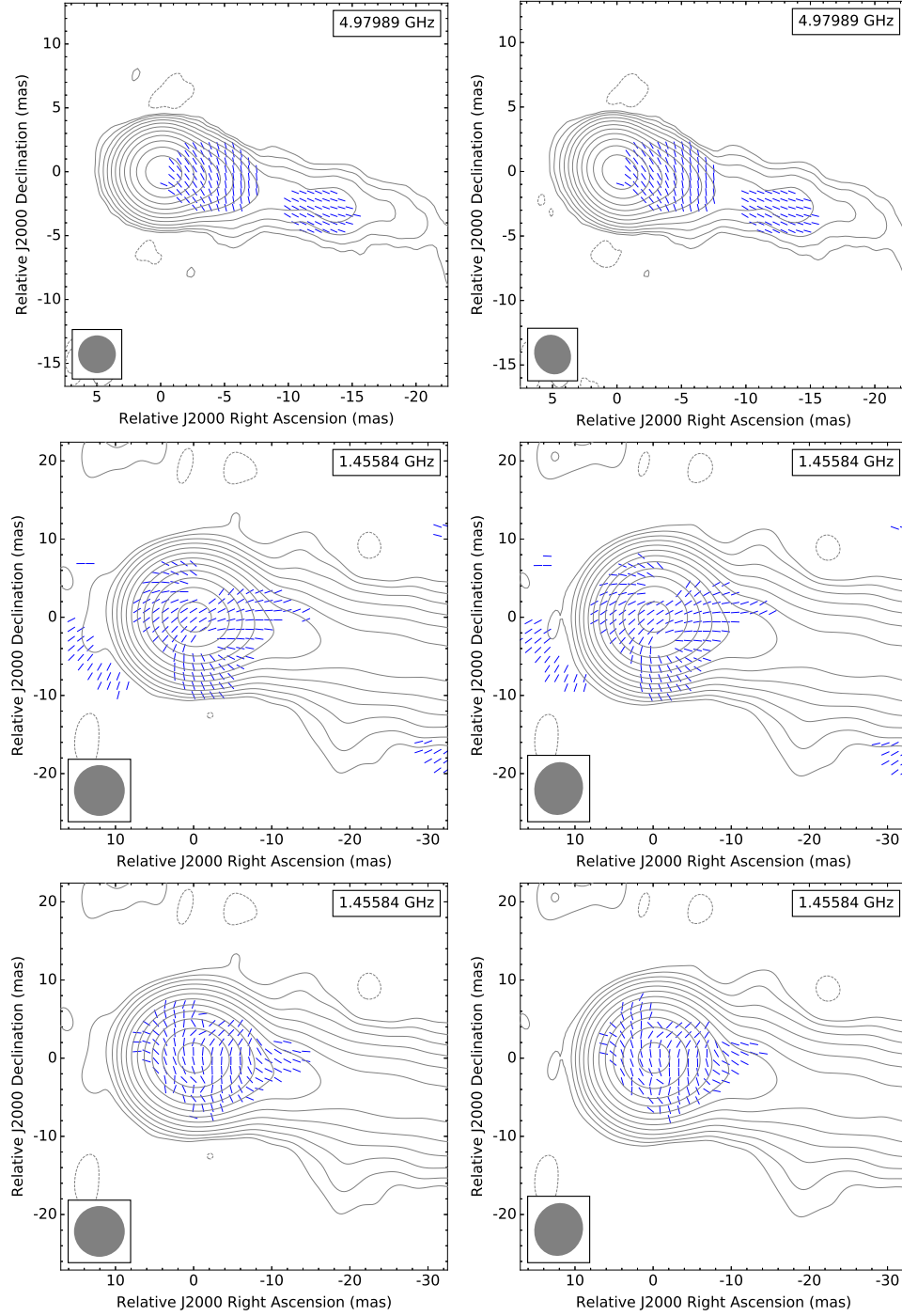


Figure 3.61: The top two panels depict the 5 GHz polarisation angle maps for J1806+6949 corrected for only the Galactic RM convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz polarisation angle maps corrected for only the Galactic RM convolved with the 1.45 GHz beam. The bottom two panels show the 1.45 GHz χ_0 maps convolved with the 1.45 GHz beams. The polarisation intensity cutoffs for the top four panels are 0.6 mJy/beam (5 GHz circular beam), 0.55 mJy/beam (5 GHz elliptical beam), 1.5 mJy/beam (1.45 GHz circular beam) and 1.5 mJy/beam (1.45 GHz elliptical beam).

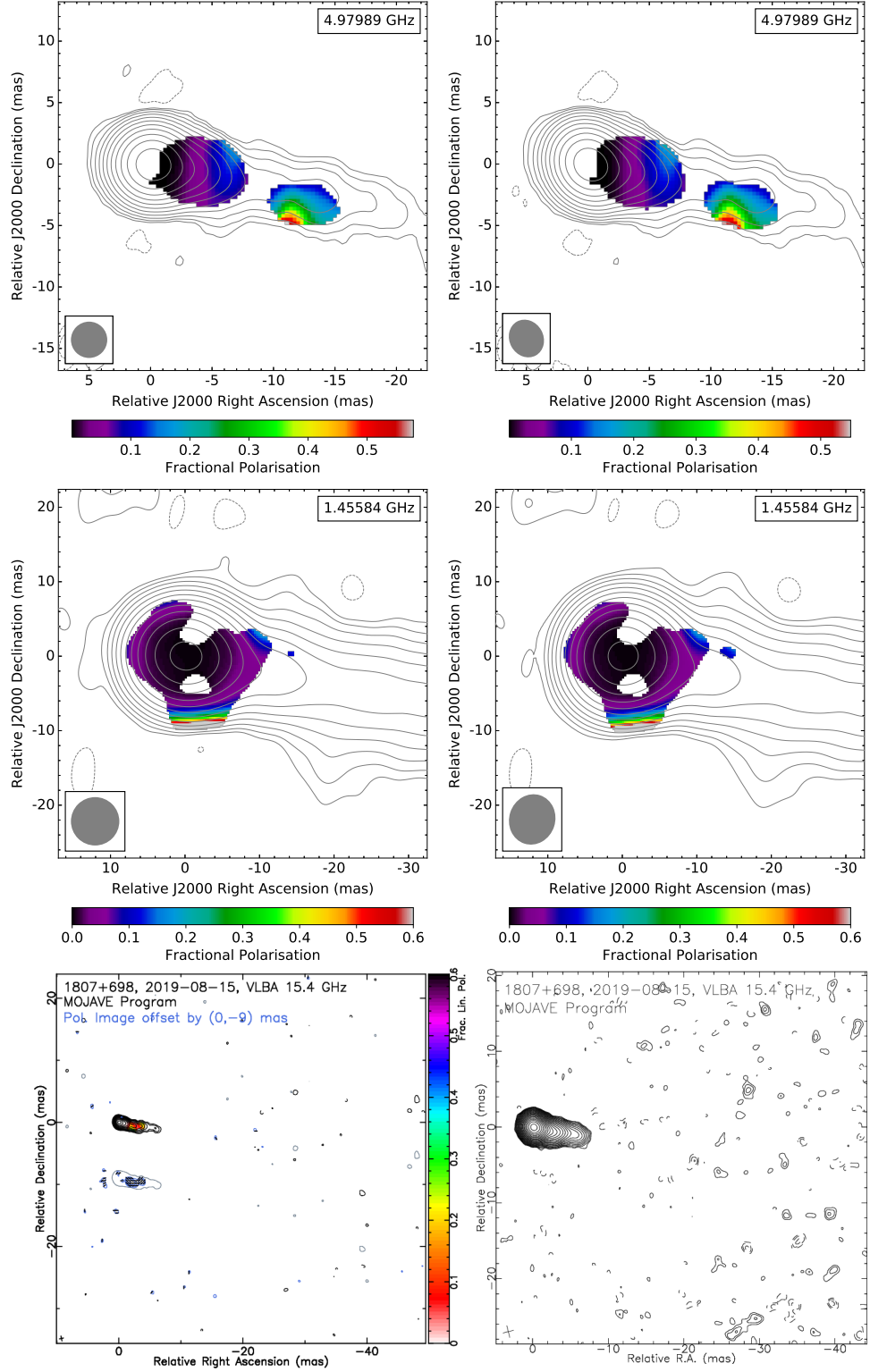


Figure 3.62: The top two panels show the 5 GHz fractional polarisation maps for J1806+6949 convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz fractional polarisation maps convolved with the 1.45 GHz beam. Polarisation intensity cutoffs are the same as in Figure 3.61. The bottom two panels show the 15 GHz MOJAVE polarisation and fractional polarisation (left) and tapered intensity (right) maps from 15/08/2019.

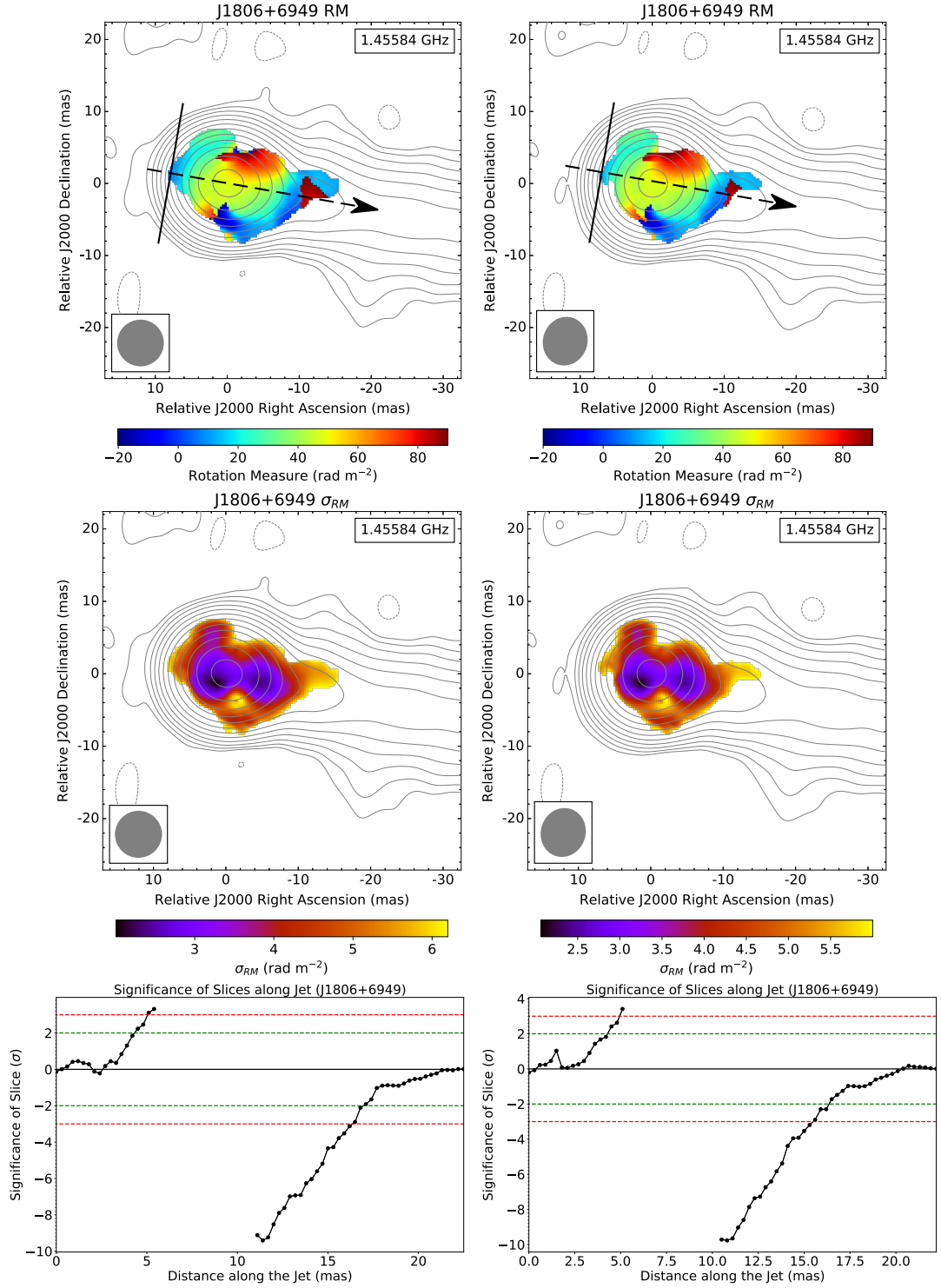


Figure 3.63: The top two panels depict the rotation measure maps for J1806+6949 convolved with the circular (left) and elliptical (right) 1.45 GHz restoring beams. The middle two panels show the corresponding error maps. The bottom two panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrow shown in the top two panels.

3.2.14 J1824+5651

J1824+5651 has a redshift of $z = 0.664$ (Lawrence et al. 1986). As can be seen in Figure 3.64, the source features a very prominent jet, heading south at an angle of $\theta \approx -160^\circ$. The spectral index map shows the expected behaviour and is consistent with the observed direction of the jet.

Most of the polarisation is localized above a relative declination of -50 mas. The 5 GHz RM_{Gal} EVPAs shown in Figure 3.65 show a clear alignment with the direction of the jet. This is consistent with other observations, such as the 15 GHz and 43 GHz MOJAVE maps, the Hovatta et al. (2012) χ_0 map, and also $\lambda = 1$ cm observations by Gabuzda & Cawthorne (2000).

The 1.45 GHz RM_{Gal} corrected EVPAs (bottom of Figure 3.65) do not reflect this alignment in the core. Due to the high sensitivity at 1.45 GHz to RM, which is proportional to wavelength squared, correcting only for RM_{Gal} is certainly insufficient near the core. Interestingly, it appears that beyond a relative declination of -20 mas the polarisation angles are orthogonal in this region. This could be a sign of a longitudinal magnetic field. Even further out (greater than 100 mas south) it appears the parallel polarisation angle alignment is seen again. Assuming this is not noise and the total RM to be relatively low here, this seems believable. The corrected χ_0 map (Figure 3.66) also shows a general alignment with the jet up to a relative declination of -10 mas then signs of being orthogonal. Overall this implies an orthogonal magnetic field in the core and inner jet, a longitudinal one further out, and possibly another region of orthogonal magnetic field in the furthest reaches of the jet.

The fractional polarisation, shown in Figure 3.67 is relatively low in the core, with $m \approx 5\%$. This increases noticeably leaving the core. In particular, the 1.45 GHz maps show an increase towards the west side of the jet. This may be associated with a bending helical field, the overlaying intensity contours showing an arc-like turn in this region.

The RM maps shown in Figure 3.68 show strong signs of a transverse RM gradient at a relative declination of about -10 mas with a significance greater than 3σ at its peak. There is the indication of a gradient in the opposite direction before this. At about 30 mas south, the jet has bent. A slice across this region gives another 3σ gradient. This is consistent with a helical magnetic field continuing down the jet. A previous 12–43 GHz study by Algaba (2013) notes a transverse RM gradient in the inner VLBI jet with the same direction as the gradient in the inner jet in Figure 3.68.

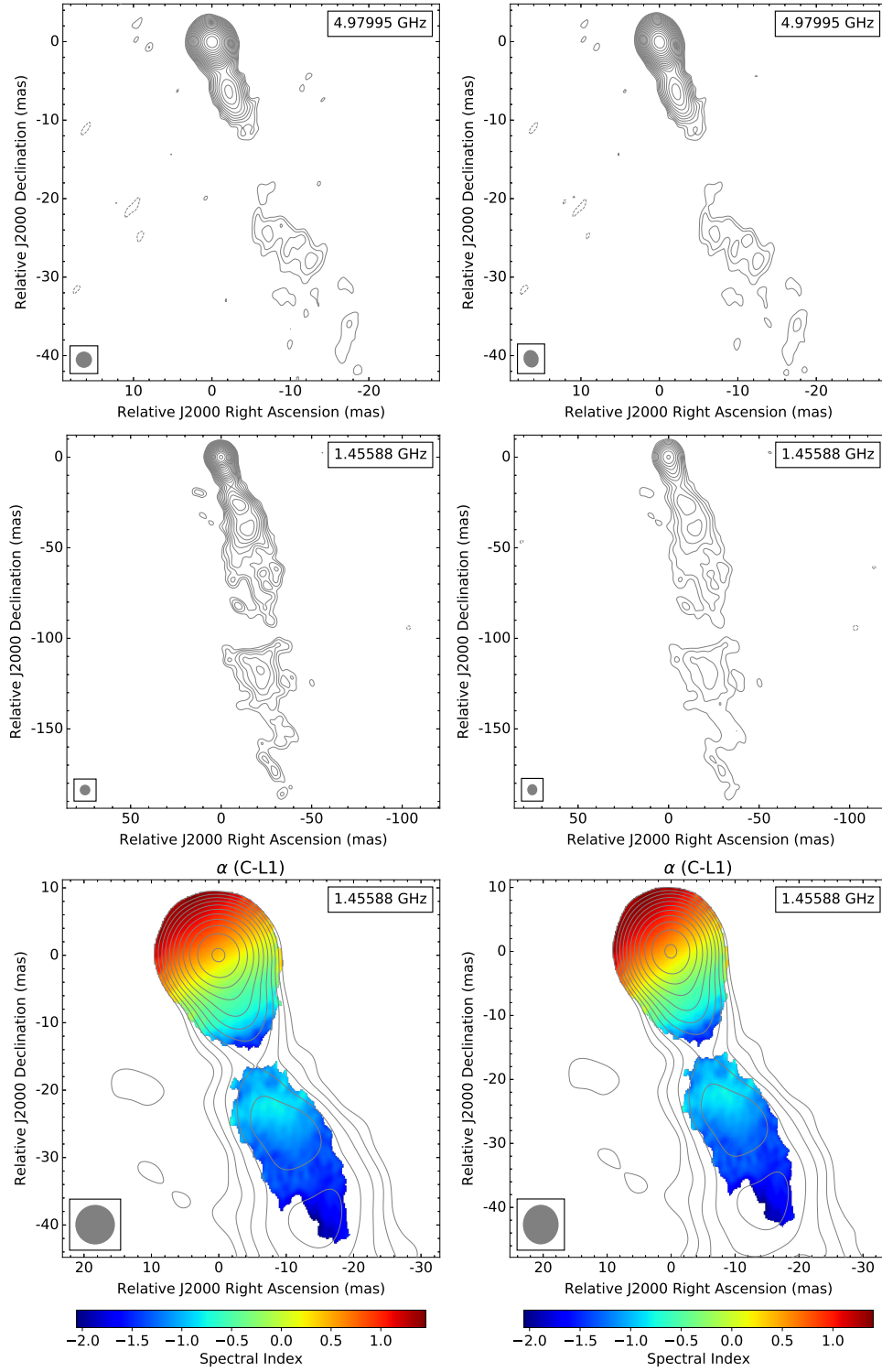


Figure 3.64: The top two panels depict the 5 GHz intensity maps for J1824+5651 convolved with the circular (left) and elliptical (right) 5 GHz beam. The middle two panels show the same for the 1.45 GHz intensity maps convolved with the 1.45 GHz beam. The bottom two panels show the C-L1 spectral index maps for J1824+5651 convolved with the 1.45 GHz beams. Intensity contours for the panels in the first two rows increase in factors of $\sqrt{2}$ and in the bottom row by factors of 2.

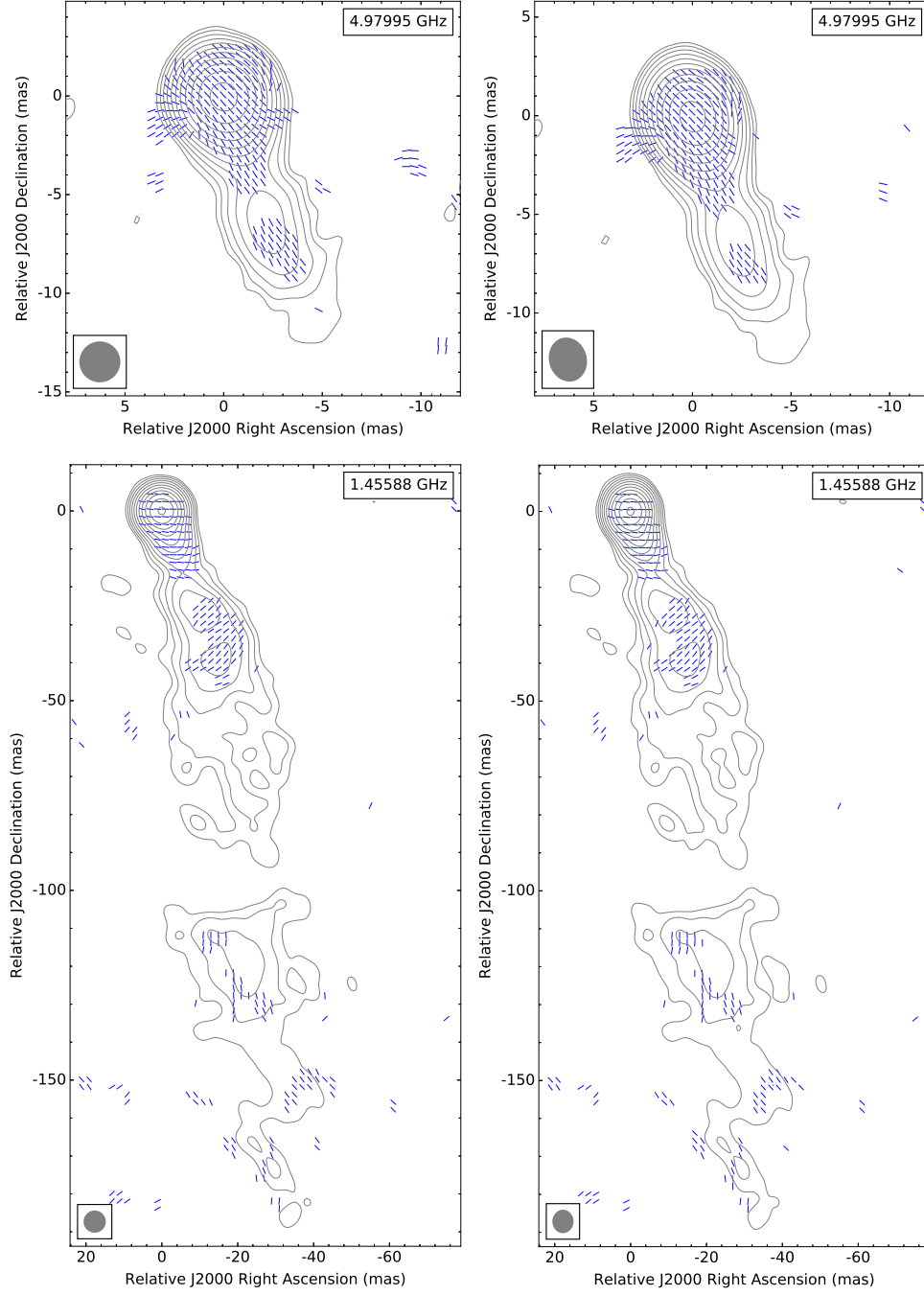


Figure 3.65: The top two panels depict the 5 GHz polarisation angle maps for J1824+5651 corrected for only the Galactic RM convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz polarisation angle maps corrected for only the Galactic RM convolved with the 1.45 GHz. The polarisation intensity cutoffs are 0.8 mJy/beam (5 GHz circular beam), 1 mJy/beam (5 GHz elliptical beam), 0.3 mJy/beam (1.45 GHz circular beam), and 0.3 mJy/beam (1.45 GHz elliptical beam).

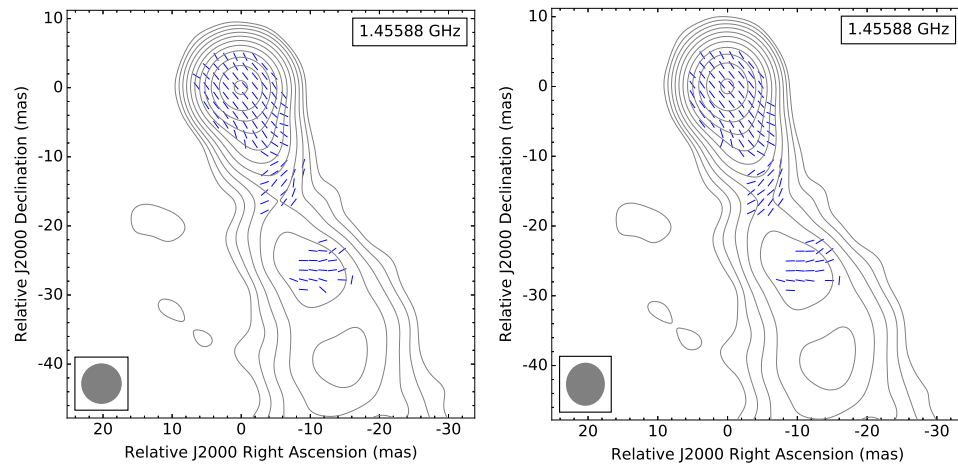


Figure 3.66: The two panels show the 1.45 GHz χ_0 maps convolved with the circular (left) and elliptical (right) 1.45 GHz beam.

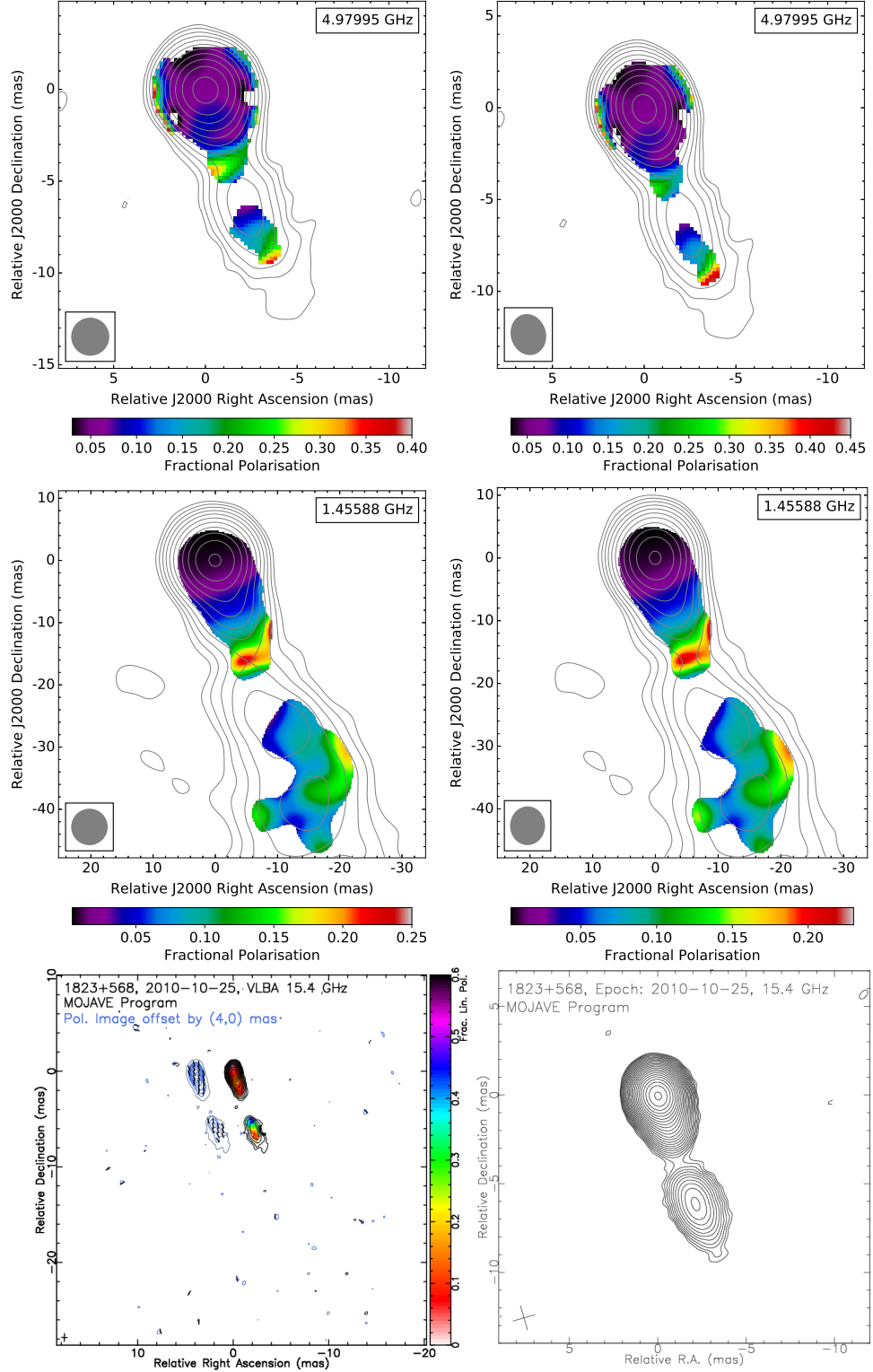


Figure 3.67: The top two panels show the 5 GHz fractional polarisation maps for J1823+5651 convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz fractional polarisation maps convolved with the 1.45 GHz beam. Polarisation intensity cutoffs are the same as in Figure 3.65. The bottom two panels show the 15 GHz MOJAVE polarisation and fractional polarisation (left) and tapered intensity (right) maps from 25/10/2010.

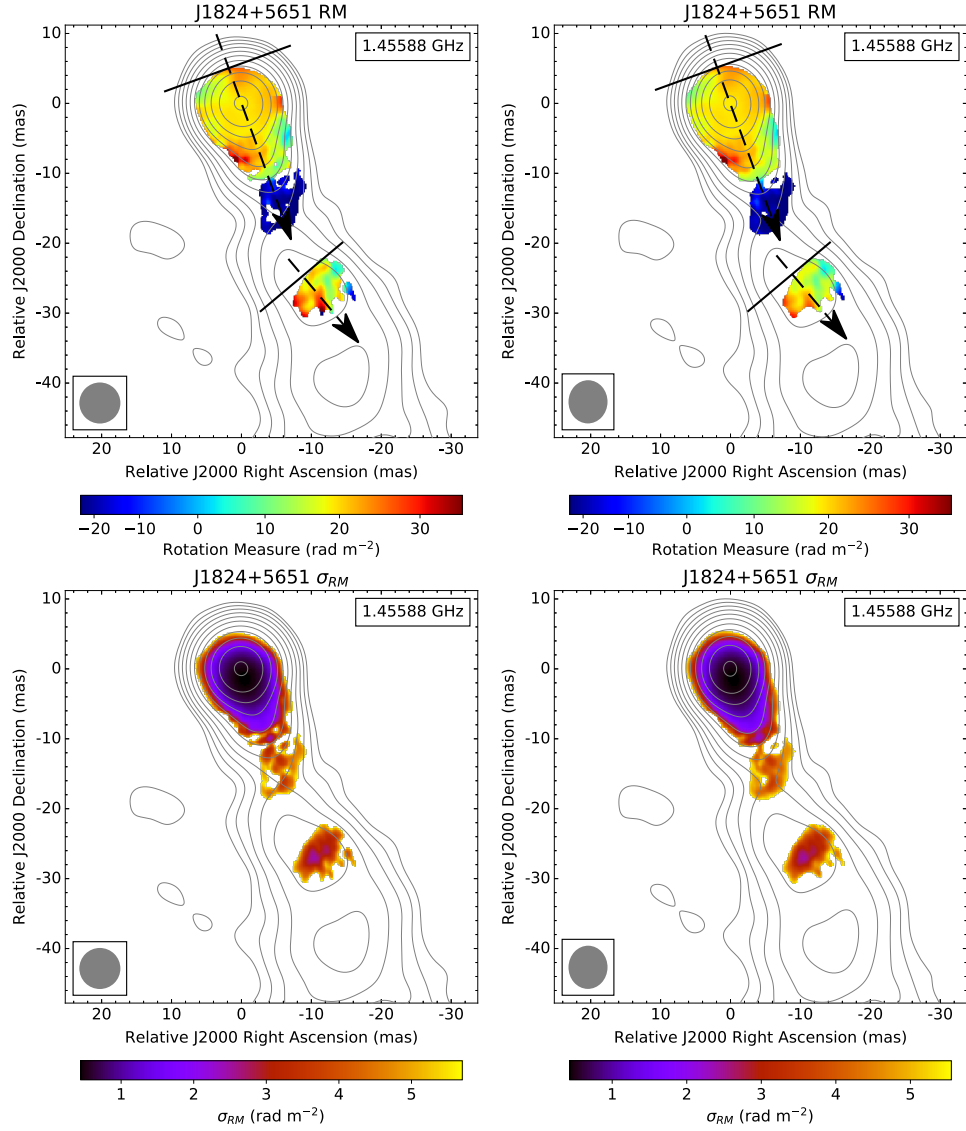


Figure 3.68: The top two panels depict the rotation measure maps for J1824+5651 convolved with the circular (left) and elliptical (right) 1.45 GHz restoring beams. The bottom two panels show the corresponding error maps. Plots of the estimated significances of the difference of the RM values on either side of the jet are shown in Figure 3.69.

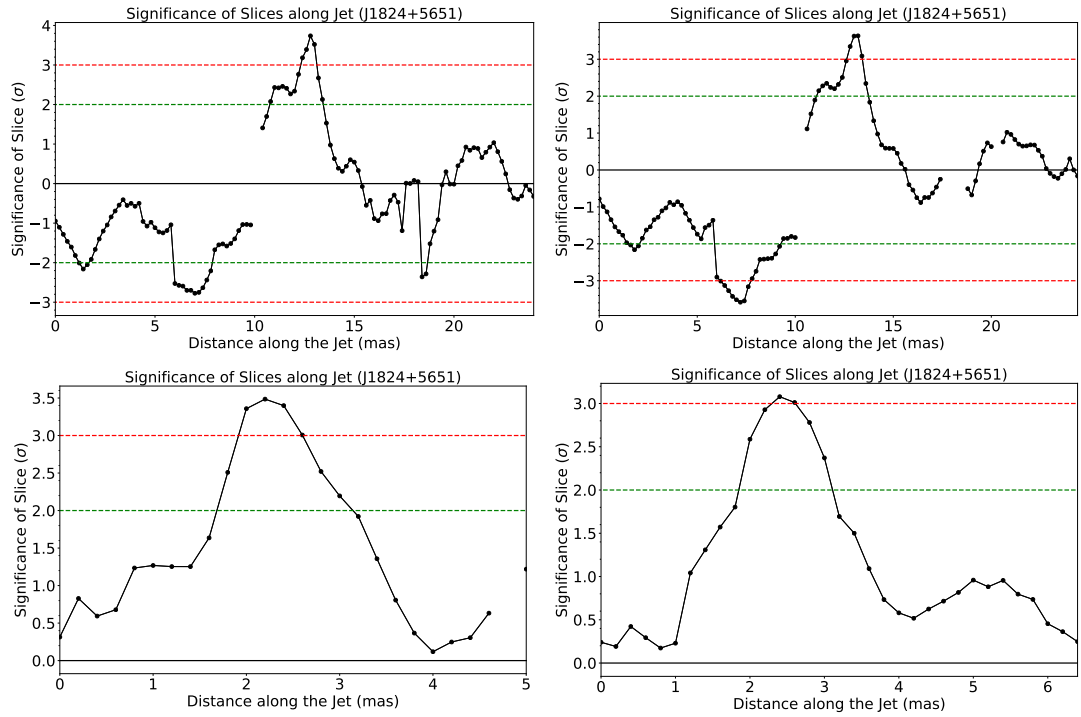


Figure 3.69: These panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrows shown in the top two panels of Figure 3.68. The top two panels of this figure are the core region and inner jet. The bottom two panels are the jet after bending, from a relative declination of roughly -22 to -30 mas.

3.2.15 J2005+7752

J2005+7752 has a redshift of $z = 0.342$ (Stickel & Fried 1989). The 15 GHz MOJAVE observations and VLBA 43 GHz observations by Cheng et al. (2020) show that the jet extends to the west, with some slight bending. In the 5 GHz and 1.45 GHz images shown in Figure 3.70, the jet direction remains steady at approximately $\theta = -95^\circ$. The spectral-index map is as expected, decreasing monotonically from the core, with the core-jet spectral-index gradient consistent with the observed jet direction.

In the Faraday corrected polarisation distribution of O’Sullivan & Gabuzda (2009), polarisation is aligned with the jet direction in the 4.6–8.9 GHz χ_0 map, supporting evidence of an orthogonal magnetic field. The inner jet and core χ_0 values implied from the 12.9–22 GHz RM map are aligned with the jet direction. In Figure 3.71, little polarisation is present outside of the core region. However, there is an indication of alignment of the polarisation with the inner jet in the 1.45 GHz RM corrected maps, consistent with the earlier findings.

Fractional polarisation shown in Figure 3.72 is fairly low in the core with $m < 5\%$. There is a noticeable increase in the 5 GHz maps on the north side, possibly due to bending at lower scales. Similarly, there is an increase on the south side in the 1.45 GHz maps. Furthermore, in the 1.45 GHz, there seems to be a correlation in fractional polarisation and increasing rotation measure, suggesting interaction with the surrounding medium.

Gabuzda et al. (2015) note a monotonic transverse RM gradient with a significance of 5.5σ . The map presented in Figure 3.73 shows two regions with transverse RM gradients. The first (north to south, negative to positive) occurs at the eastern edge of the RM distribution. As this only has a significance greater than 3σ when convolved with the circular beam, it is considered tentative. The next, more distinct gradient occurs slightly after the peak of radio intensity (relative right ascension of approximately -4 mas). This has a much greater significance, greater than 5σ in both maps. The direction of this later transverse RM gradient is the same as that detected earlier by Gabuzda et al. (2015)

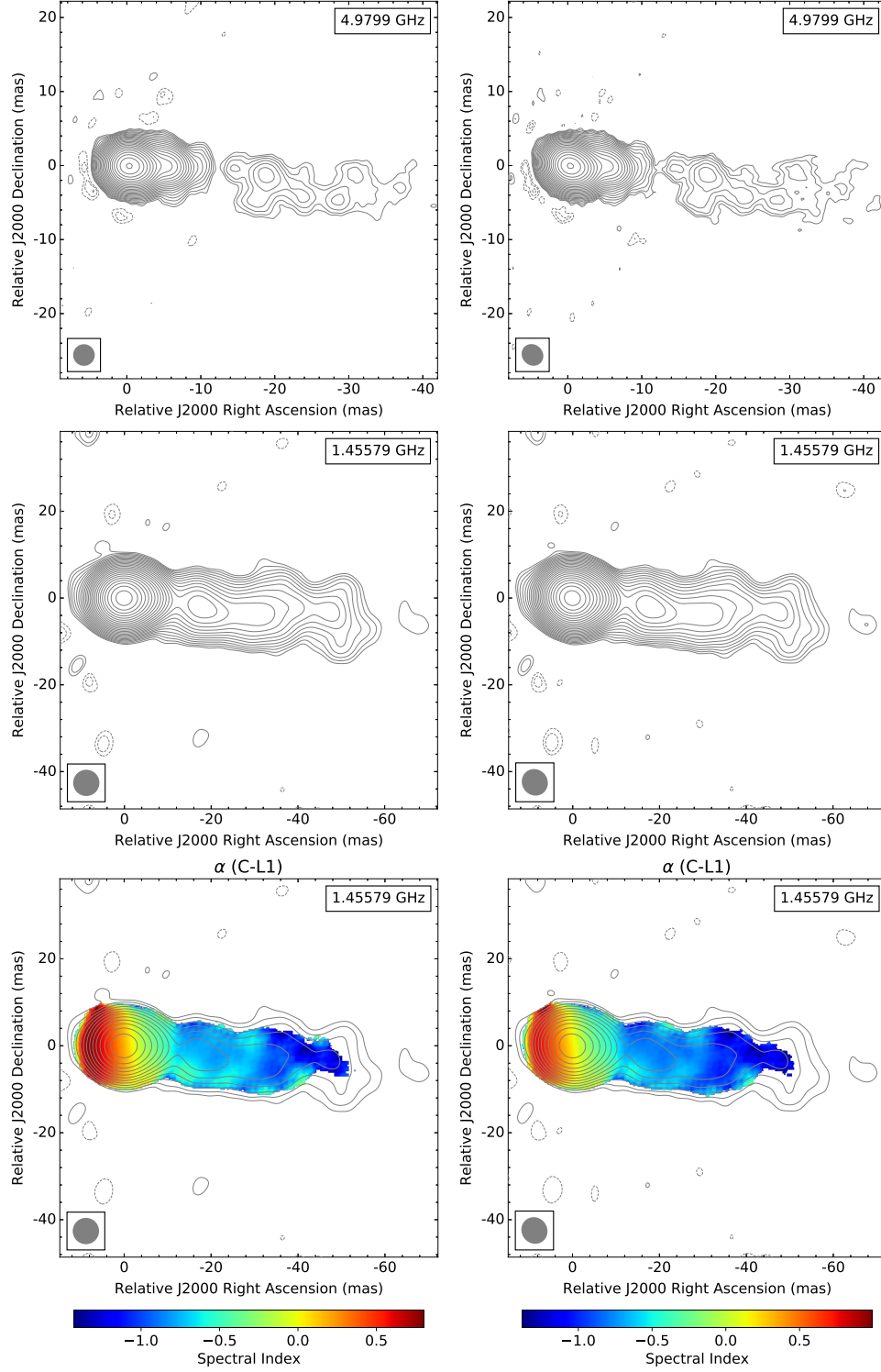


Figure 3.70: The top two panels depict the 5 GHz intensity maps for J2005+7752 convolved with the circular (left) and elliptical (right) 5 GHz beam. The middle two panels show the same for the 1.45 GHz intensity maps convolved with the 1.45 GHz beam. The bottom two panels show the C–L1 spectral index maps for J2005+7752 convolved with the 1.45 GHz beams. Intensity contours for the panels in the first two rows increase in factors of $\sqrt{2}$ and in the bottom row by factors of 2.

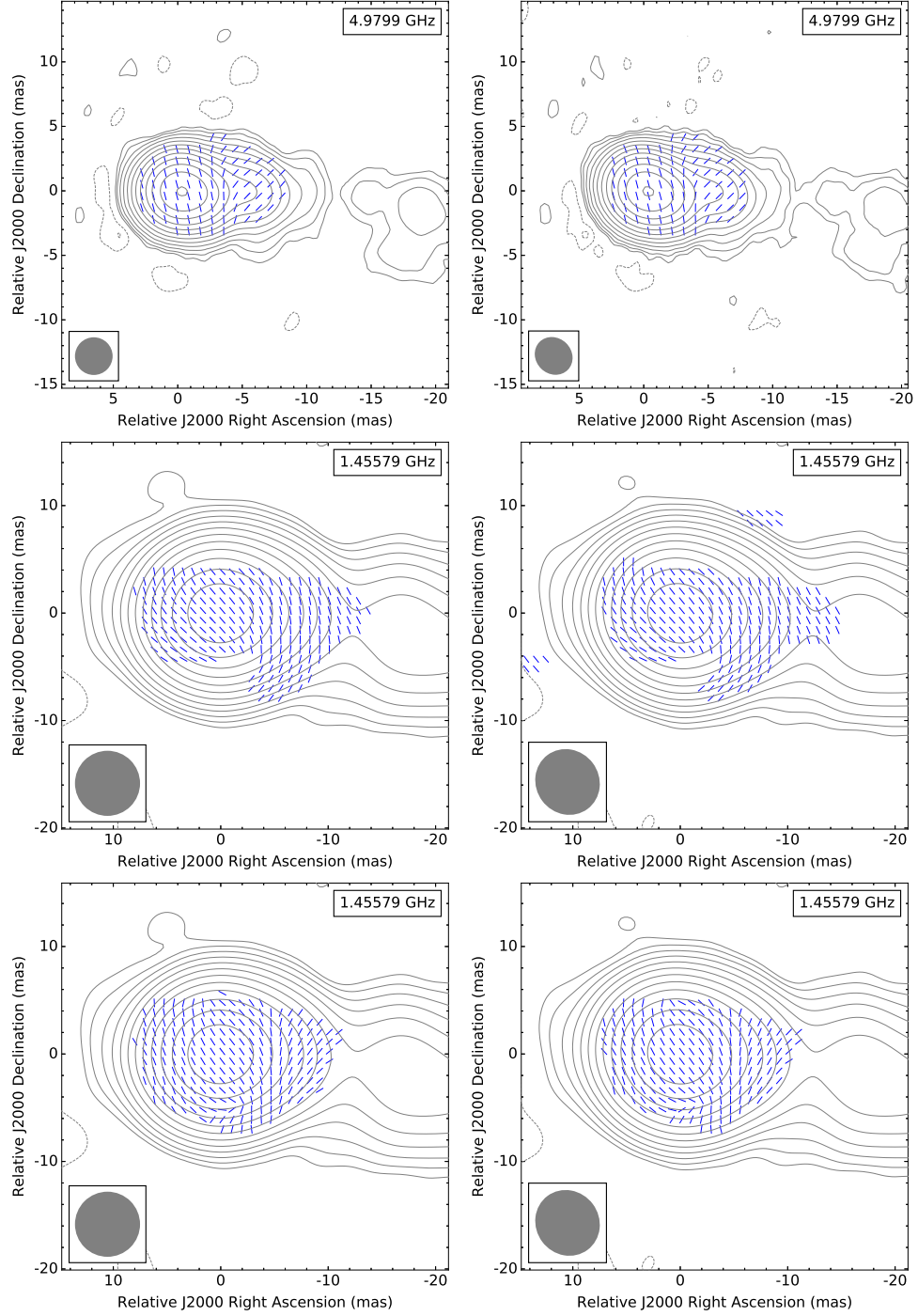


Figure 3.71: The top two panels depict the 5 GHz polarisation angle maps for J2005+7752 corrected for only the Galactic RM convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz polarisation angle maps corrected for only the Galactic RM convolved with the 1.45 GHz beam. The bottom two panels show the 1.45 GHz χ_0 maps convolved with the 1.45 GHz beams. The polarisation intensity cutoffs for the top four panels are 0.4 mJy/beam (5 GHz circular beam), 0.43 mJy/beam (5 GHz elliptical beam), 1.75 mJy/beam (1.45 GHz circular beam) and 1.85 mJy/beam (1.45 GHz elliptical beam).

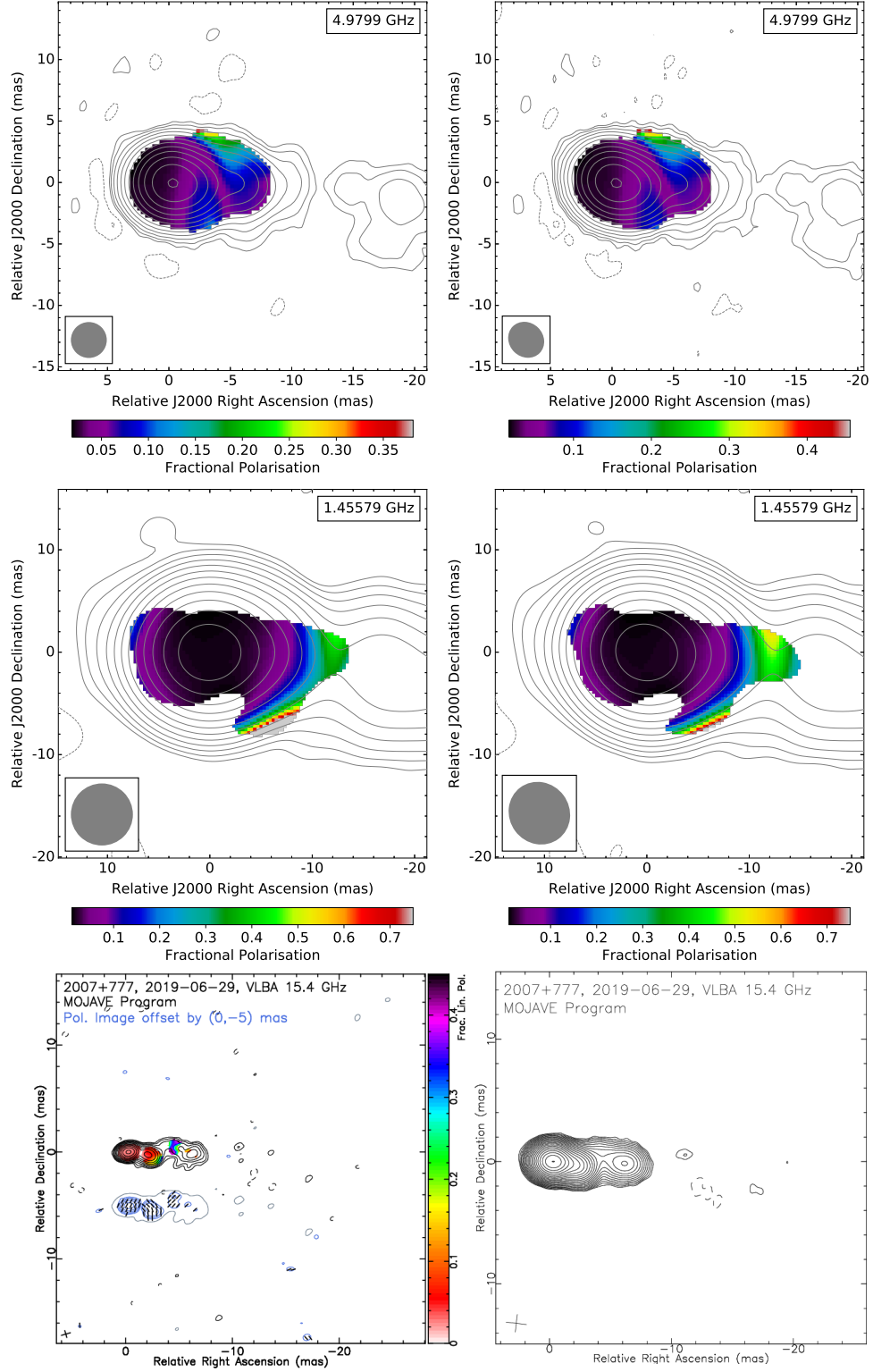


Figure 3.72: The top two panels show the 5 GHz fractional polarisation maps for J2005+7752 convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz fractional polarisation maps convolved with the 1.45 GHz beam. Polarisation intensity cutoffs are the same as in Figure 3.71. The bottom two panels show the 15 GHz MOJAVE polarisation and fractional polarisation (left) and tapered intensity (right) maps from 29/06/2019.

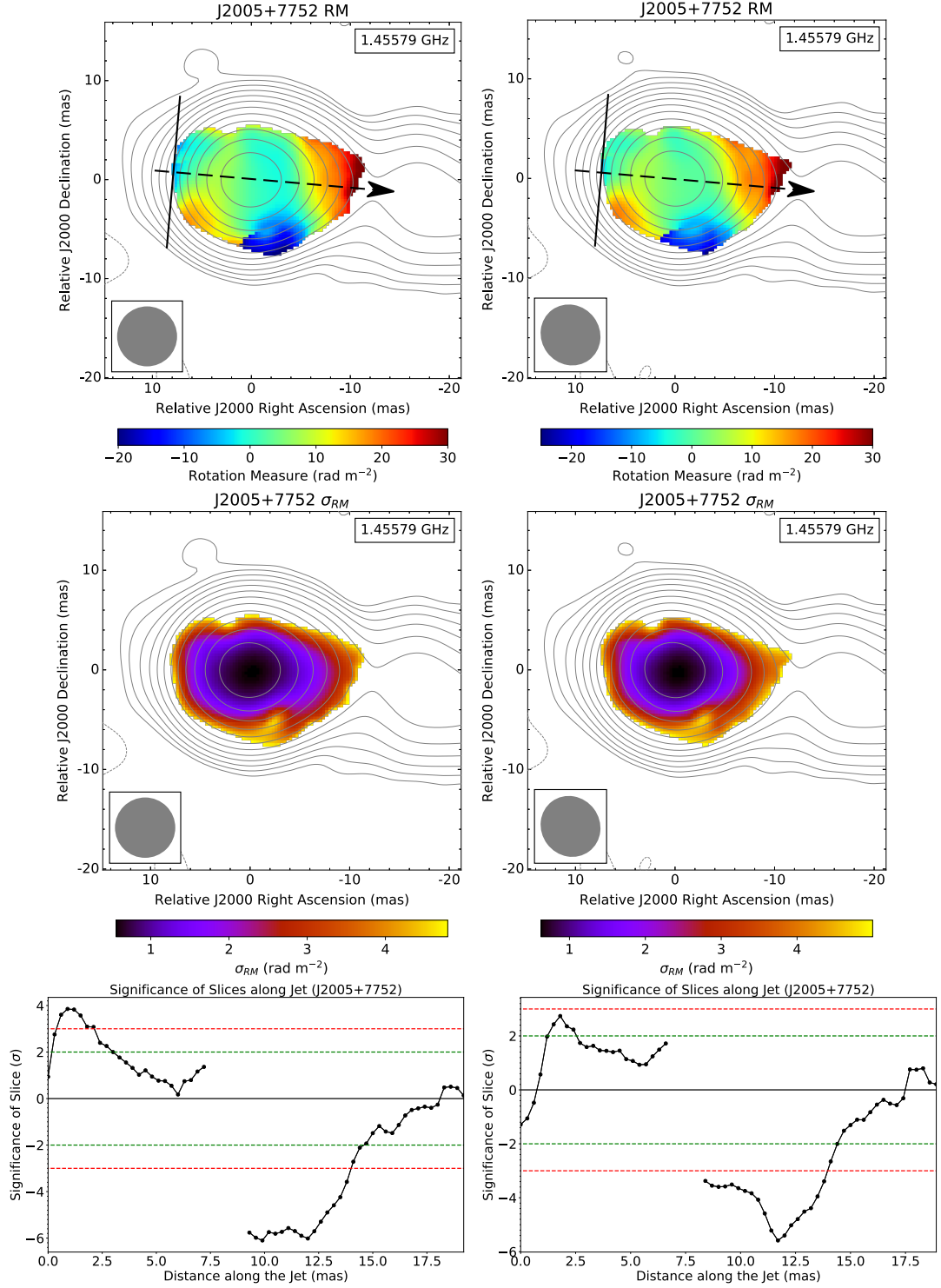


Figure 3.73: The top two panels depict the rotation measure maps for J2005+7752 convolved with the circular (left) and elliptical (right) 1.45 GHz restoring beams. The middle two panels show the corresponding error maps. The bottom two panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrow shown in the top two panels. Due to high noise in the L2 band data, these panels were made only using polarisation data from the C, S, and L1 bands.

3.2.16 J2202+4216

J2202+4216, (common name BL Lac) has a low redshift of $z = 0.0686$ (Vermeulen et al. 1995). It is a compact source and the first BL Lac object ever discovered by Cuno Hoffmeister in 1929. BL Lac is highly variable at radio wavelengths, changing on timescales of days. As can be seen in the 15, 23, and 43 GHz MOJAVE observations, the jet extends south at an angle of $\theta = -175^\circ$ until approximately 10 mas from the core, where the jet continues to the south-east before becoming diffuse. This is seen in the 5 GHz observations of Figure 3.74. However, it is difficult to see this inner structure on the larger 1.45 GHz scale. The core-jet gradient in the spectral-index map is consistent with the observed direction of the inner jet.

Studies of the polarisation structure of BL Lac at higher frequencies (for example O’Sullivan & Gabuzda (2009), the 15 GHz and 23 GHz MOJAVE maps, and the Hovatta et al. (2012) χ_0 map), find that the EVPAs are aligned with the jet direction along the spine, indicating a magnetic field which is orthogonal to the jet direction. In addition, a tentative spine-sheath structure was identified in Healy (2013). In Figure 3.75, a spine-sheath structure, possibly indicative of a helical magnetic field, is seen in the 5 GHz polarisation maps, with parallel polarisation down the jet and orthogonal alignment at the edges. This is also displayed in the 1.45 GHz maps, especially the χ_0 maps, which supports the findings of Healy (2013).

Previous fractional polarisation maps of BL Lac such as Hallahan & Gabuzda (2008) show how the fractional polarisation in the jet of BL Lac increases both with distance from the core and towards the jet edge. Likewise, in the fractional polarisation maps in Figure 3.76, the degree of polarisation can be seen to increase away from the core and towards the jet edges. Little polarisation is detected in the central core region. The jet shows polarisation between values of 10% and 20%. The increase in fractional polarisation at the jet edges can either be interpreted as indicative of a helical magnetic field or the result of interaction with the surrounding medium.

The 4.6–15.4 GHz study of Gabuzda et al. (2017) yielded 2 regions of likely transverse RM gradients in the inner jet. A 16–22 cm study by Motter & Gabuzda (2017) also displayed a single gradient across the core, although located in the opposite direction and located near the peak. A small-scale study at 21 μ as resolution by Gómez et al. (2016) also showed a transverse gradient in the core.

In the results presented in Figure 3.77, a possible (significance of $\approx 3\sigma$) transverse gradient exists in the core region. The orientation is consistent with Gabuzda et al. (2017) although it does not seem entirely uniform, the RM difference mostly

stemming a thin band along the edge. Realistically this would be considered tentative. An interesting feature in Figure 3.77 is the increase in RM detected at the southern RM region where the jet bends, possibly indicating interaction with the surrounding medium. It is possible, that the predominant direction of the transverse RM gradients in J2202+4216 may vary with time.

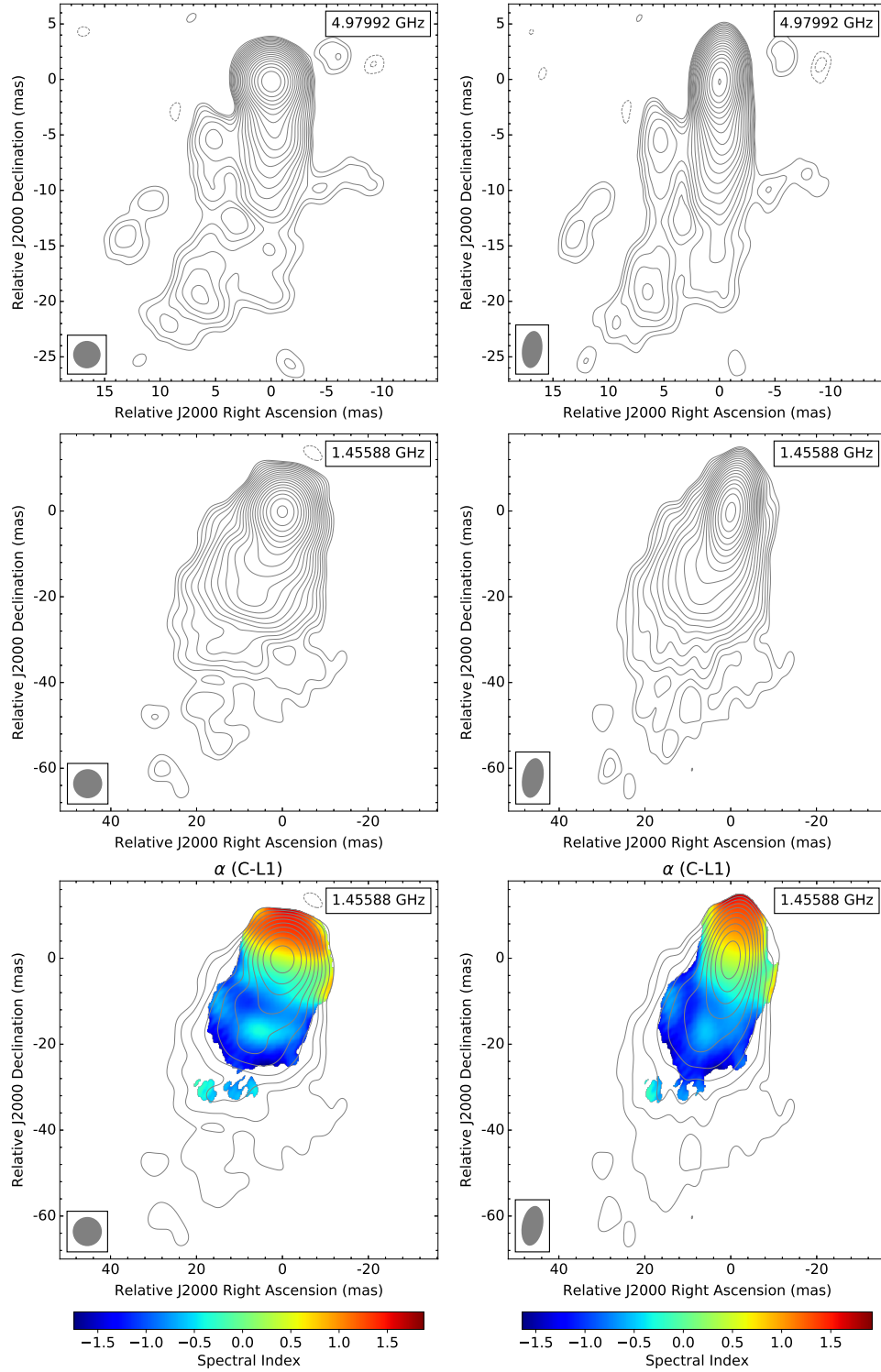


Figure 3.74: The top two panels depict the 5 GHz intensity maps for J2202+4216 convolved with the circular (left) and elliptical (right) 5 GHz beam. The middle two panels show the same for the 1.45 GHz intensity maps convolved with the 1.45 GHz beam. The bottom two panels show the C-L1 spectral index maps for J2202+4216 convolved with the 1.45 GHz beams. Intensity contours for the panels in the first two rows increase in factors of $\sqrt{2}$ and in the bottom row by factors of 2.

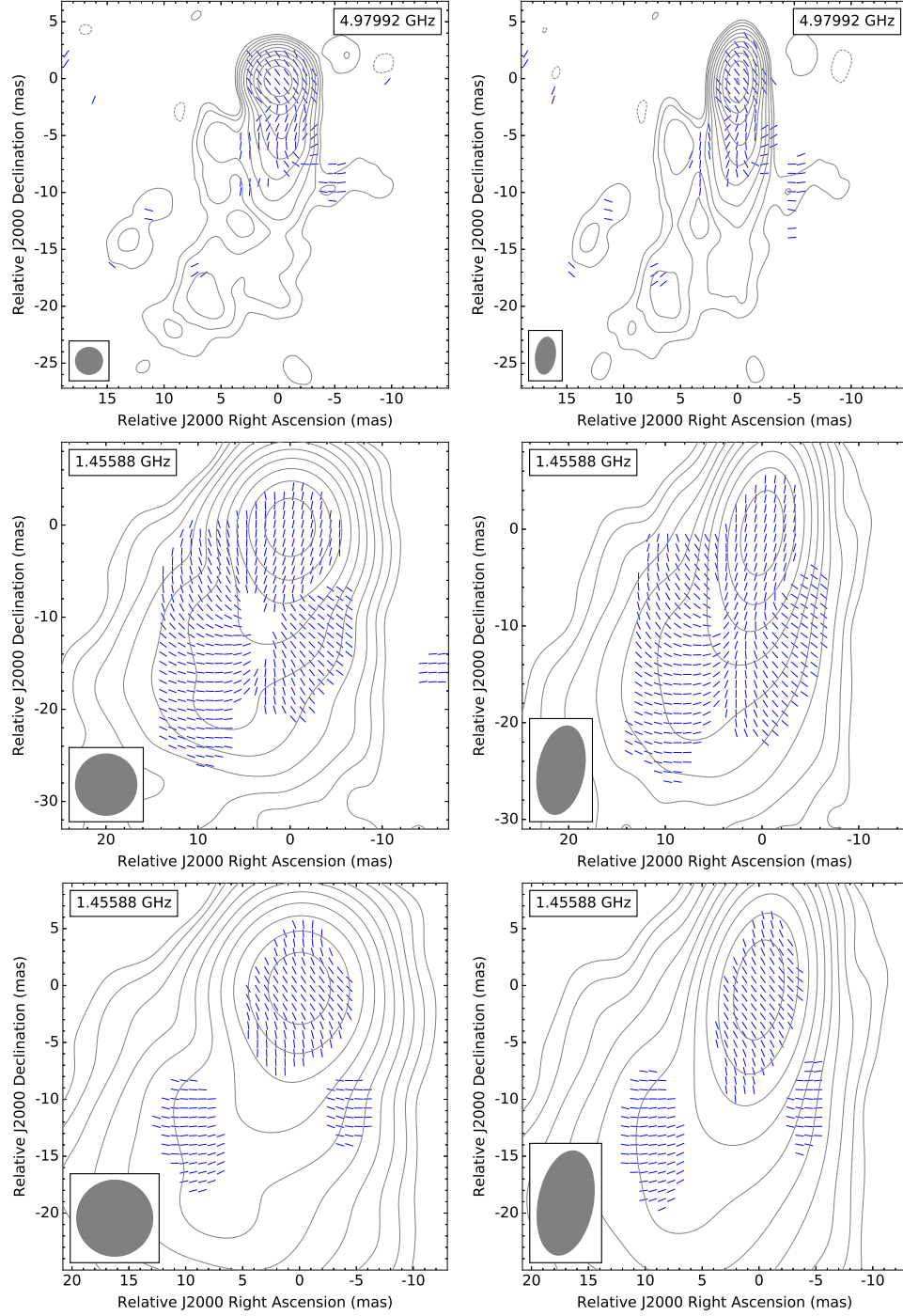


Figure 3.75: The top two panels depict the 5 GHz polarisation angle maps for J2202+4216 corrected for only the Galactic RM convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz polarisation angle maps corrected for only the Galactic RM convolved with the 1.45 GHz beam. The bottom two panels show the 1.45 GHz χ_0 maps convolved with the 1.45 GHz beams. The polarisation intensity cutoffs for the top four panels are 0.96 mJy/beam (5 GHz circular beam), 0.975 mJy/beam (5 GHz elliptical beam), 1 mJy/beam (1.45 GHz circular beam) and 1.25 mJy/beam (1.45 GHz elliptical beam).

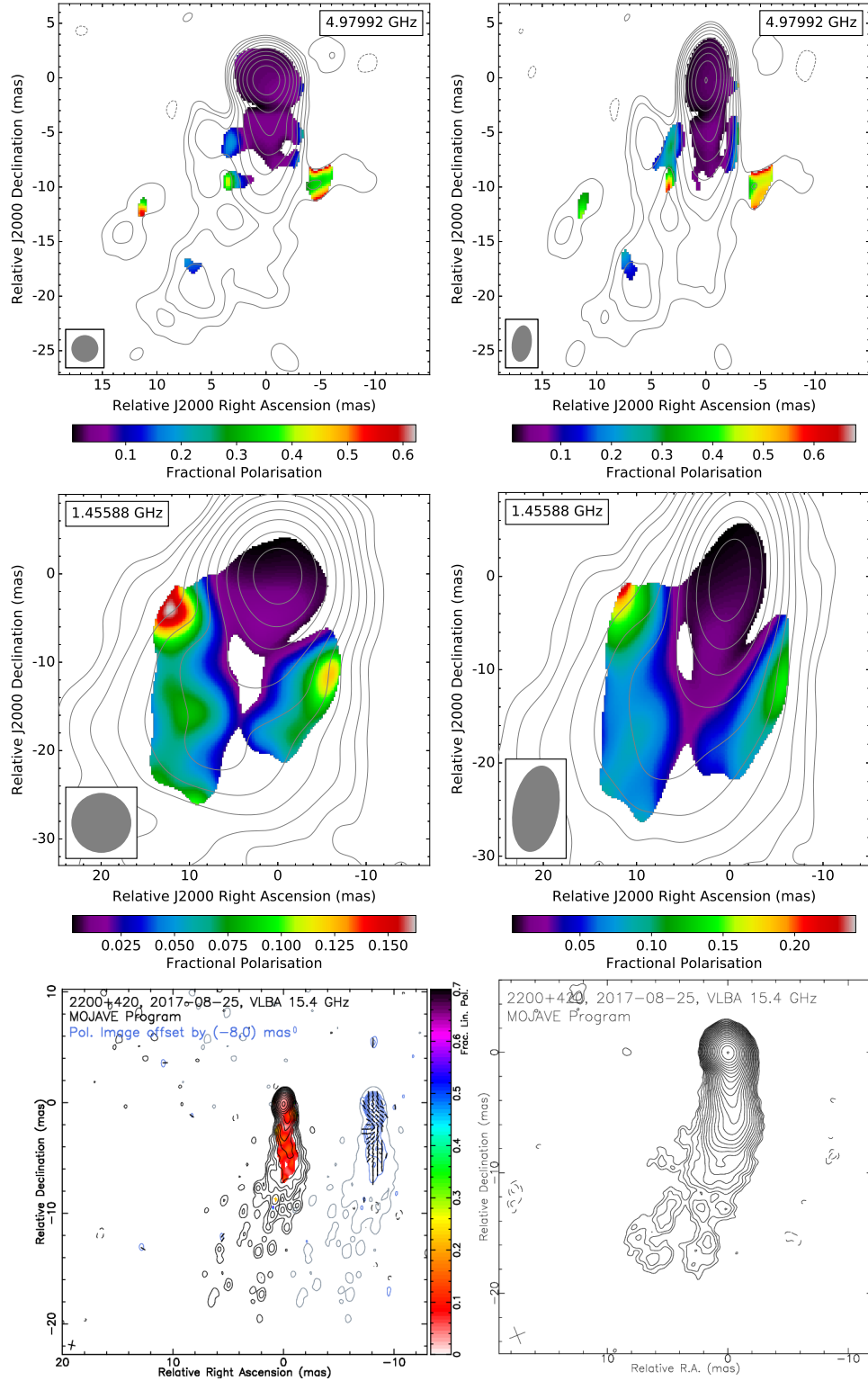


Figure 3.76: The top two panels show the 5 GHz fractional polarisation maps for J2202+4216 convolved with the circular (left) and elliptical (right) 5 GHz beams. The middle two panels show the same for the 1.45 GHz fractional polarisation maps convolved with the 1.45 GHz beam. Polarisation intensity cutoffs are the same as in Figure 3.75. The bottom two panels show the 15 GHz MOJAVE polarisation and fractional polarisation (left) and tapered intensity (right) maps from 25/08/2017.

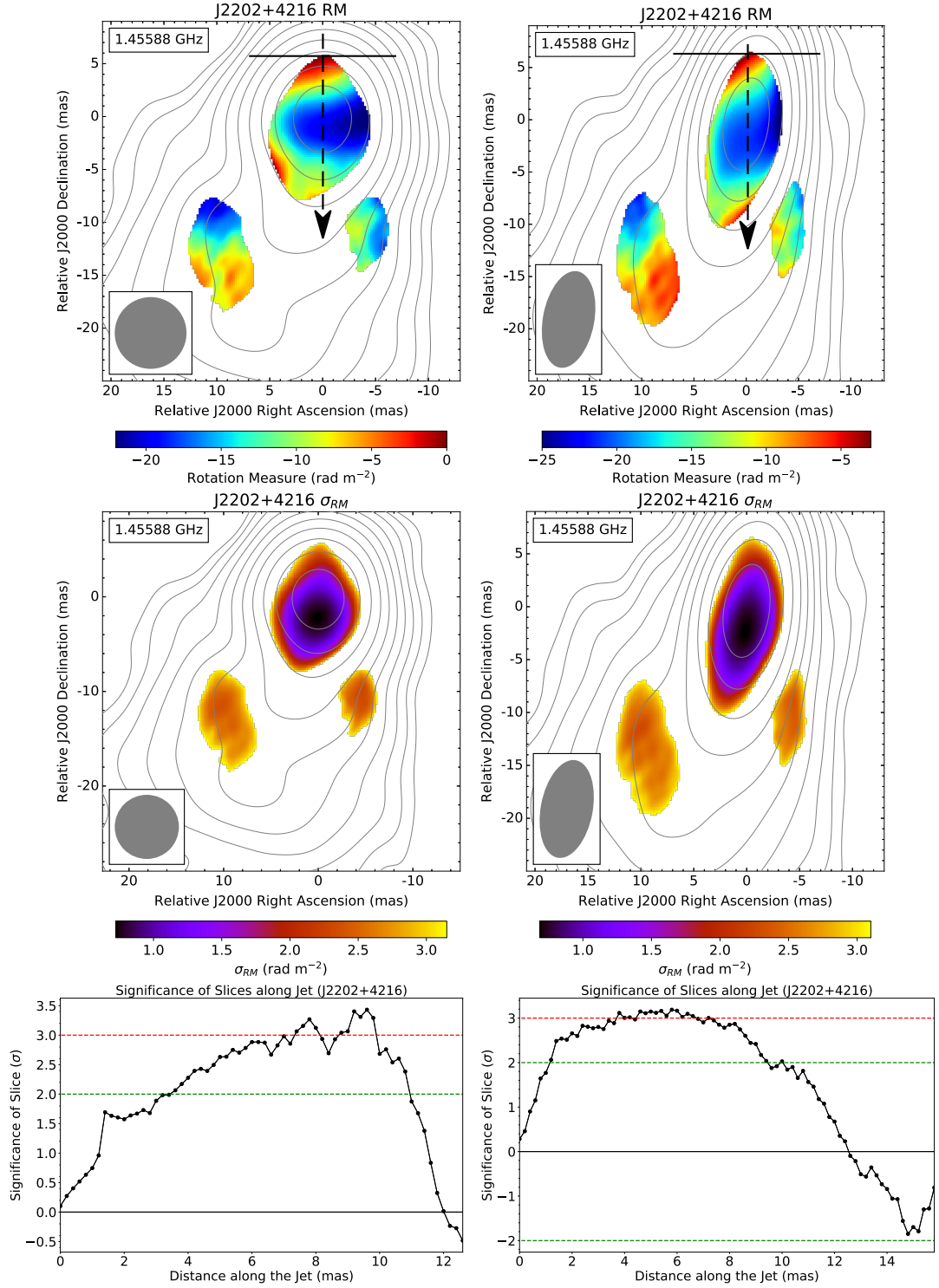


Figure 3.77: The top two panels depict the rotation measure maps for J2202+4216 convolved with the circular (left) and elliptical (right) 1.45 GHz restoring beams. The middle two panels show the corresponding error maps. The bottom two panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrow shown in the top two panels.

3.3 Summary of Results

In this chapter, 1.45, 1.8, 2.2, and 5 GHz VLBA polarisation observations of 16 BL Lac objects made in 2017 and 2019 were presented. Their morphology, EVPA structure, fractional polarisation, and Faraday rotation measure distribution were discussed.

3.3.1 Polarisation Structure

Both J0738+1742 and J2202+4216 (BL Lac) showed tentative signs of a spine-sheath structure in the distribution of their polarisation angles, indicating the possible presence of a helical magnetic field.

The jets of J1800+7828, J1806+6949, and J1824+5651 feature strong evidence of alignment of polarisation angles parallel to the jet direction all along their lengths, indicating an orthogonal magnetic field. J0721+7120, J0818+4222, J0958+6533, and J2005+7752 indicated this in their inner jet. The sources J0748+2400 and J1824+5651 show strong signs of a sustained longitudinal field with polarisation angles aligned perpendicular to the jet. In particular, J0748+2400, J1824+5651 and also possibly J0006-0623 show separate regions with both parallel and perpendicular alignment. The localized regions of entirely parallel or orthogonal alignment may indeed be interpreted as possessing helical fields as explained in Murphy et al. (2013) but further study is needed.

Very little polarisation structure was visible in the jets of J0050-0929, J0121+1149, J0825+0309, J0854+2006, and J1751+0939, with any polarisation mainly confined to the core region. In these cases, insufficient data was present to draw any conclusion about the presence of a spine-sheath structure or other polarisation structure that would provide evidence for a helical magnetic field. However, consistency between the 5 GHz EVPAs (which are not affected greatly by any RM) and the 1.45 GHz χ_0 map provides good evidence for the accuracy of the fit obtained in the RM map itself.

3.3.2 Fractional Polarisation

The plausibility of the spine-sheath polarisation structures in sources J0738+1742 and J2202+4216 and a possible helical field model was strengthened by a clear increase in fractional polarisation away from the core and towards the edges of both sides of the jet for both of these sources.

J1800+7828 shows a region with increasing m towards both sides and a region of parallel EVPA alignment. J0006-0623, J0748+2400, J0958+6533, J1800+7828, J1806+6949, and J1824+5651 also displayed an increase in fractional polarisation towards one side in at least one of the two presented frequencies in regions with parallel EVPA, (or in the case of J0006-0623 and J0748+2400, orthogonal) alignment with the jet. Again, this is only partial evidence for a helical field.

Although not linked to a helical field, J2005+7752 and J2202+4216 showed interesting increases in fractional polarisation coupled with an increase in RM indicating a link between these quantities. J0121+1149 and J0721+7120 also displayed localized fractional polarised increases that could just as likely be associated with a shock. The remaining sources did not display interesting fractional polarisation but all 16 sources showed the core region to have low fractional polarisation, as expected in a partially optically thick region.

3.3.3 Faraday Rotation Measure

Convincing and statistically significant (significance exceeding 3σ) transverse RM gradients were detected in eleven sources (J0006-0623, J0050-0929, J0121+1149, J0748+2400, J0818+4222, J0958+6533, J1800+7828, J1806+6949, J1824+5651, J2005+7752 and J2202+4216). This is another piece of evidence supporting toroidal or helical fields.

The presence of such RM gradients for J0748+2400, J0958+6533, J1800+7828, J1806+6949, J1824+5651, J2005+7752, and J2202+4216 in addition to the suitable EVPA and fractional polarisation structure discussed earlier, strengthens the argument for these particular sources possibly having a helical field. Within these sources, there are also segments of debatable authenticity (significance $> 2\sigma$ but less than 3σ). Future studies at these scales may confirm these or rule them out. Furthermore, some sources, such as J1800+7828, J1824+5651, and maybe J0818+4222 or J2005+7752 show interesting reversals within their RM distributions. This is not a requirement for a helical field but it indicates a more complex structure suitable for further study. The most plausible explanation for the presence of such reversals in the direction of transverse RM gradients is a “nested-helix” model, as is discussed in Mahmud et al. (2013). Although they may have been statistically significant the gradients calculated in J0738+1742, J0825+0309, J0854+2006, and J1751+0939 were not monotonic, uniform, and dependent on pixels at one edge and considered spurious.

Chapter 4

Comparison with Older Observations

4.1 Introduction

The results shown in this thesis are from observations made between 2017 and 2019 and at a wavelength range of 6 to 21 cm. In addition, VLBA observations for the same sources were made in 2004 and 2010 at four wavelengths over a range of 18 to 22 cm. The wavelengths used in these datasets were 22.1, 21.0, 20.1, and 18.0 cm (or in terms of frequency 1.35, 1.43, 1.49, and 1.66 GHz). The purpose of this chapter is to compare the results of this thesis with these older observations. Not all 16 sources were included in both of these datasets but the following chapter will examine all available data.

All the following maps were made using the 1.45 GHz circular beam used earlier in the 6 to 21 cm observations to enable proper comparison in morphology and structure. Comparison will mostly be done between the L1 band maps (1.45 GHz) from the more recent observations and the 1.43 GHz observations from 2004 and 2010 as these frequencies are the most similar. No major change in morphology was expected between the older and newer epochs. It was also expected that there would be no change in EVPA outside the core.

Most of the figures in this chapter have three columns and four rows of panels. The three columns show results for 2004, 2010, and 2017/2019, from left to right. The four rows show, from top to bottom, the 1.45 or 1.43 GHz polarisation, 1.45 or 1.43 GHz fractional polarisation, rotation measure, and rotation measure error. When the earlier data are available at only 2004 or only 2010, the figures have the same structure, but only two columns of panels. The year for each figure panel is shown in

the panel header. In all cases, the 2004, 2010, and 2017/2019 images for a given source are shown using the same ranges for the fractional polarisation and rotation measure. Note that no alignment was needed between the four images obtained from the 2004 and 2010 observations since the four wavelengths are too close to lead to significant shifts. In all cases, the same estimated Galactic rotation measure was subtracted from the 2004, 2010, and 2017/2019 RM maps. When plots of the significance of transverse RM gradients are shown, these are given as separate figures.

4.2 Results

4.2.1 J0006-0623

There were no significant changes in morphology between the 2017 observations and either the 2004 or 2010 observations. The EVPAs very clearly show a double structure at both 2004 and 2010. The EVPA distributions at the three epochs are quite different, possibly due to different relative strengths of the core and jet emission at different epochs. The core region seems to be dominated by a region with nearly vertical polarisation in 2004 and 2017.

The fractional polarisation maps are also consistent over the three datasets with $m < 15\%$ across the distribution. In the 2004 and 2010 maps, there appears to be a drop in fractional polarisation coinciding with the "gap" between the first and second components of the double structure, apparently due to cancellation of polarisation with roughly perpendicular directions in the core and jet regions.

The 2004 rotation measure map shows a vertical streak of increased rotation measure at the termination of the first component of the double structure, whose origin is not clear. There is a modest increase in the RM uncertainties at the location of this feature, but the uncertainties don't seem high enough to make this feature completely spurious. The jet RM values are very similar at 2010 and 2017, while the jet RM values for 2004 are appreciably different. The core RM values vary significantly from epoch to epoch. Neither the 2004 nor the 2010 rotation measure maps show clear evidence for transverse RM gradients.

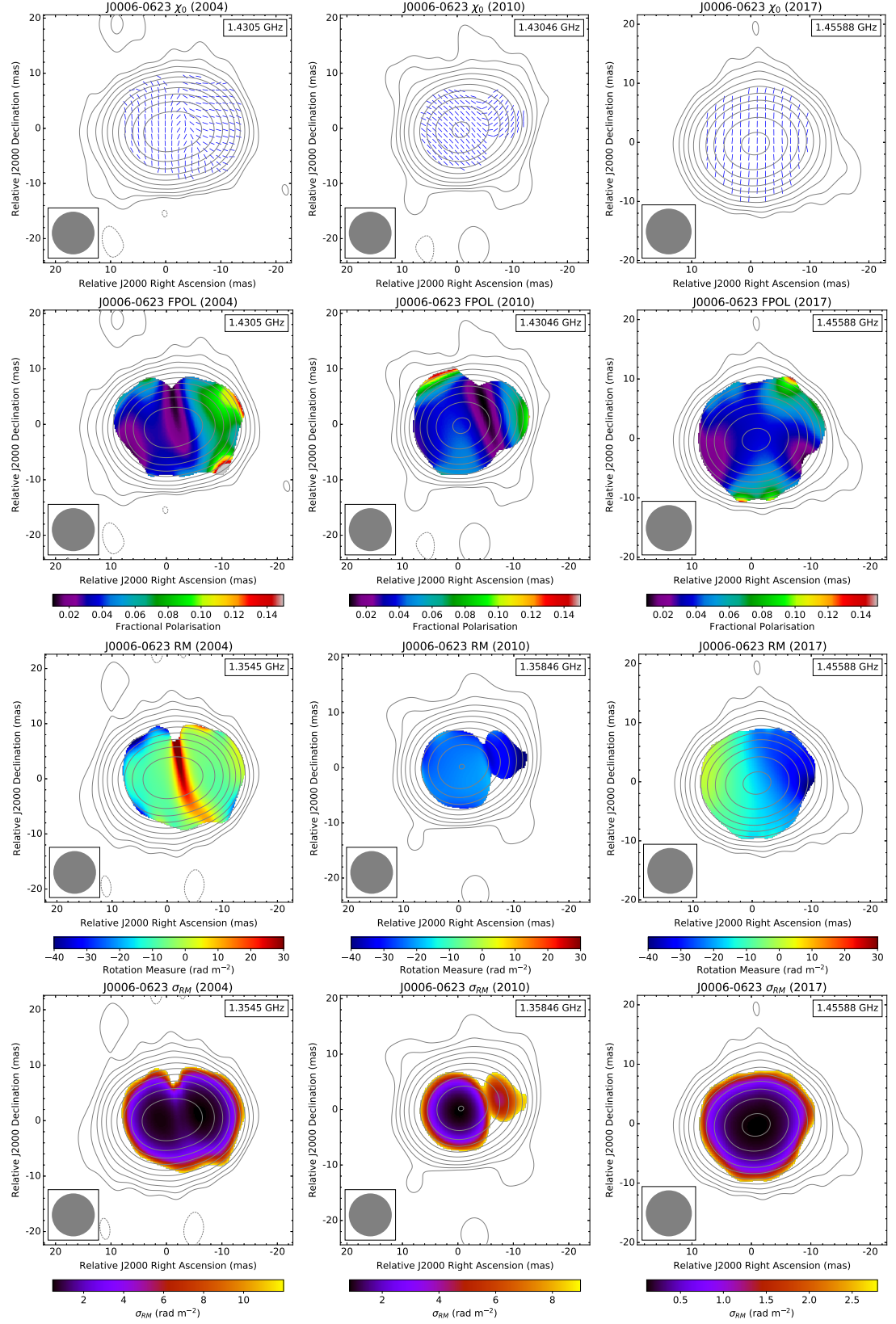


Figure 4.1: See the description of figures at the end of Section 4.1.

4.2.2 J0050-0929

There were no significant changes in morphology between the 2017 observations and either the 2004 or 2010 observations. The polarisation structure detected in J0050-0929 is mostly limited to the core. The χ_0 EVPAs in the core region in 2004 are uniformly at $\chi = 0^\circ$, lie in $\chi = -45^\circ$ in 2010, and in $\chi = +45^\circ$ in 2017. The jet polarisation is relatively weak, but the EVPAs to the northeast and northwest of the core are similar in 2010 and 2017, possibly corresponding to polarisation at the inner jet edges.

The fractional polarisation maps across the three epochs consistently show a core region with $m < 5\%$. The 2010 and 2017 fractional polarisation maps show a similar structure, with the fractional polarisation increasing on the easterly side of the jet. This may be a result of bending, possible interaction with the intergalactic medium, or a helical jet magnetic field, but the polarisation is weak, and it may also be spurious.

The three RM maps show significantly different values in and across the core region. The 2004 rotation measure map, shows a possible transverse gradient, the significance of which is shown in Figure 4.3 and exceeds 3σ . However, the gradient is not entirely monotonic and the result arguably arises mainly due to high values at the western edges. It does however mirror the more reliable 2017 transverse RM gradient. The 2010 rotation measure map shows no evidence at all for a transverse gradient.

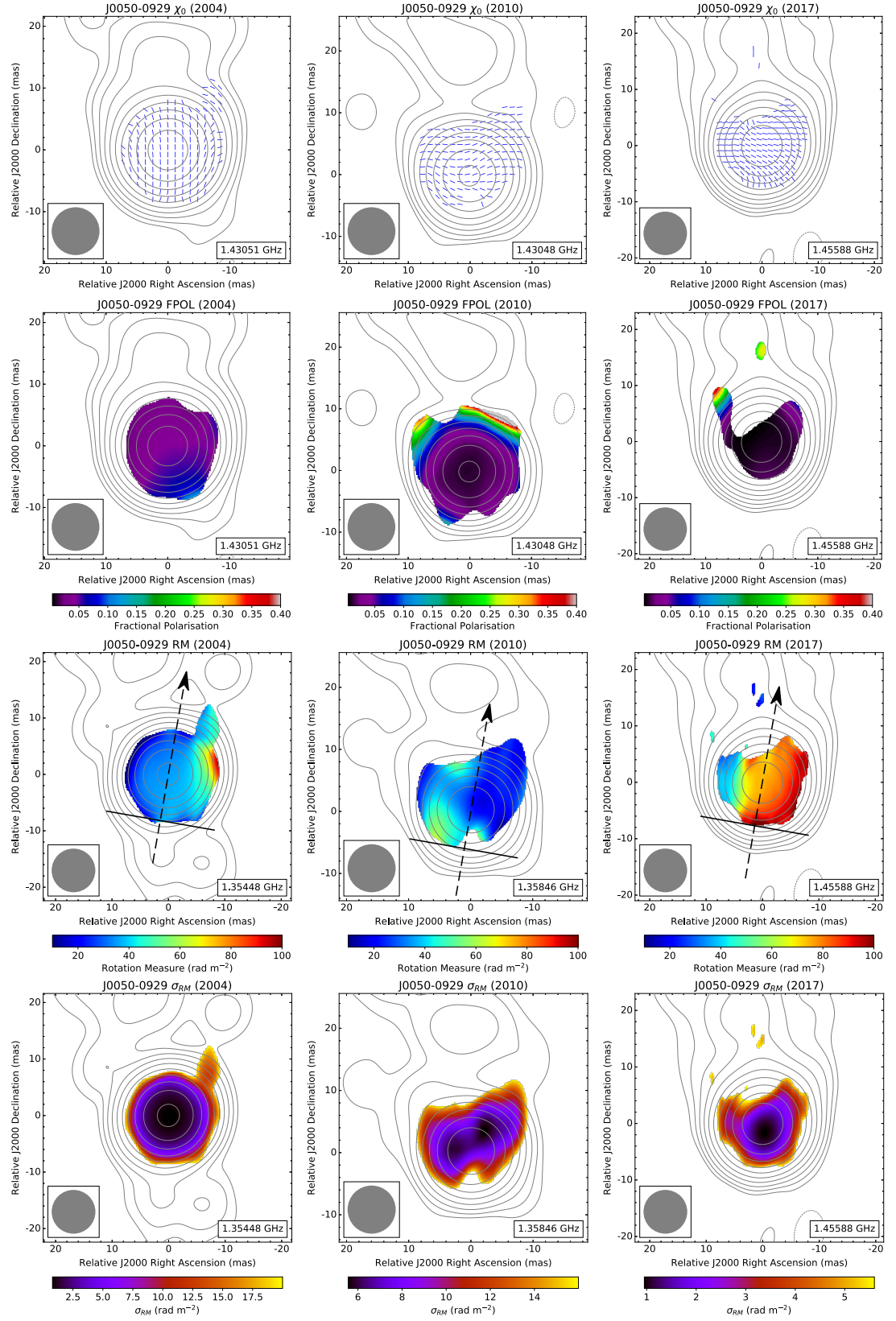


Figure 4.2: See the description of figures at the end of Section 4.1.

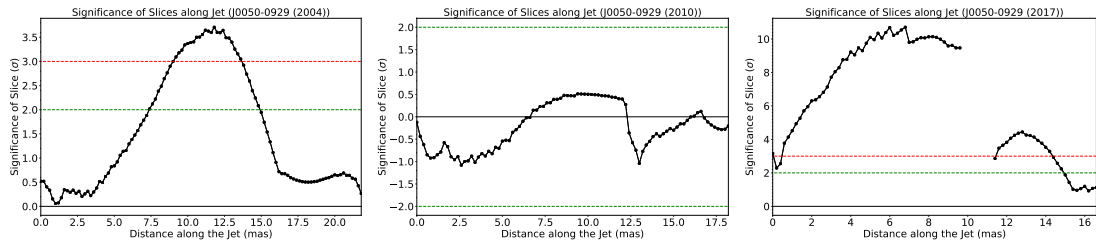


Figure 4.3: These panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrows shown in the third row of Figure 4.2. Left panel: 2004 epoch, Middle panel: 2010 epoch, Right panel: 2017 epoch.

4.2.3 J0121+1149

The morphology of J0121+1149 remains the same in 2017 as in the 2004 and 2010 epochs, the jet extending approximately 80 mas to the east and 60 mas north overall. The 2004 and 2010 data were previously looked at by Coughlan et al. (2011). The polarisation in 2017 was mostly restricted to the core, however, this is not the case for the 2004 and 2010 epochs which show polarisation extending along the jet. This is most likely due to higher levels of noise and interference in the 2017 data.

The distribution of polarisation angles is complex. The intrinsic (χ_0) polarisation angles differ in the core and jet over all three epochs.

Both the 2004 and 2010 fractional polarisation maps show low polarisation ($m < 5\%$) in the core, consistent with the 2017 maps, this increases upwards of 20%, going north and out of the core. The 2010 map, in particular, shows increasing fractional polarisation towards the western jet edge, a possible sign of a helical magnetic field or interaction with an ambient medium.

Coughlan et al. (2011) did not allow for sufficient $n\pi$ rotations in the EVPAs for this source leading to incorrect rotation measure values in the jet. Avoiding this error, the Faraday rotation maps for 2004 and 2010 display 3 distinct regions: the core, inner jet, and outer jet. Only the core region is present in 2017. No evidence of any transverse rotation measure gradients is detected at either of the earlier epochs. The RM range in this core region is roughly consistent at all three epochs, and the RM values in the outer jet are similar in 2004 and 2010. The RM values in the inner jet region are higher in 2010 compared to 2004, suggestive of a change in the thermal electron density in this region between the two epochs.

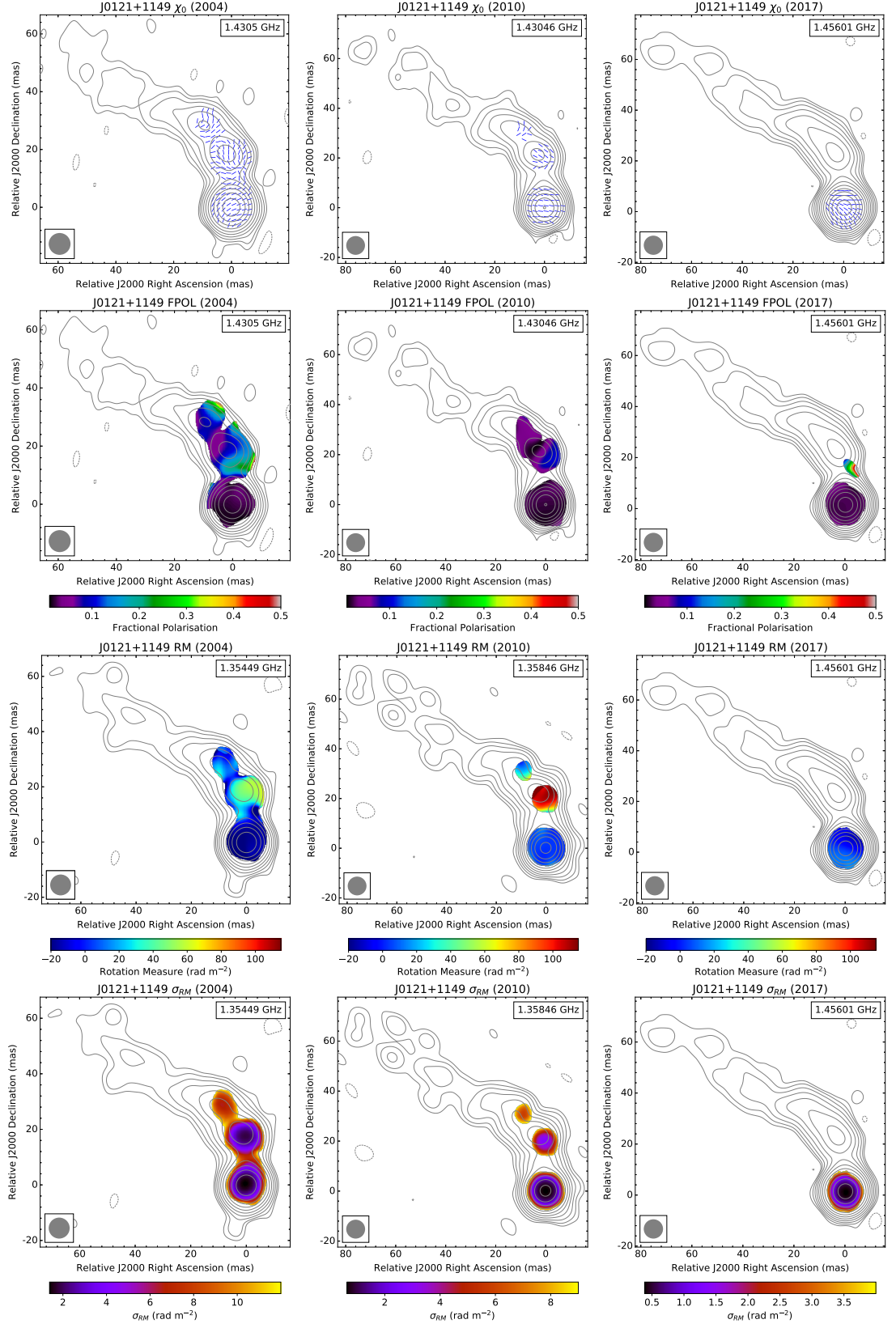


Figure 4.4: See the description of figures at the end of Section 4.1.

4.2.4 J0721+7120

There appears to be little significant change in morphology or polarisation structure between the 2004, 2010, and 2017 observations of J0721+7120. The 2004 and 2010 data were considered earlier (Healy 2013). No polarisation was detected in the jet at any epoch beyond 15 mas north.

There is consistent evidence of alignment of polarisation angles with the inner jet at all three epochs. This is consistent with an orthogonal field in this region. The fractional polarisation increases to more than 30% in the inner jet. It shows a distinct increase toward one edge of the jet, but this is the eastern edge in 2004 and the western edge in 2010.

The rotation measure maps maintained similar values overall with values between 0 and 30 rad m^{-2} . The 2004 and 2010 rotation measure maps show possible transverse RM gradients, but in opposite directions, as was noted by Healy (2013). More monitoring would be needed to determine whether the change in the side of higher fractional polarisation and the change in the direction of the transverse RM gradients are related. Unfortunately, the 2017 RM map adds little information to this picture.

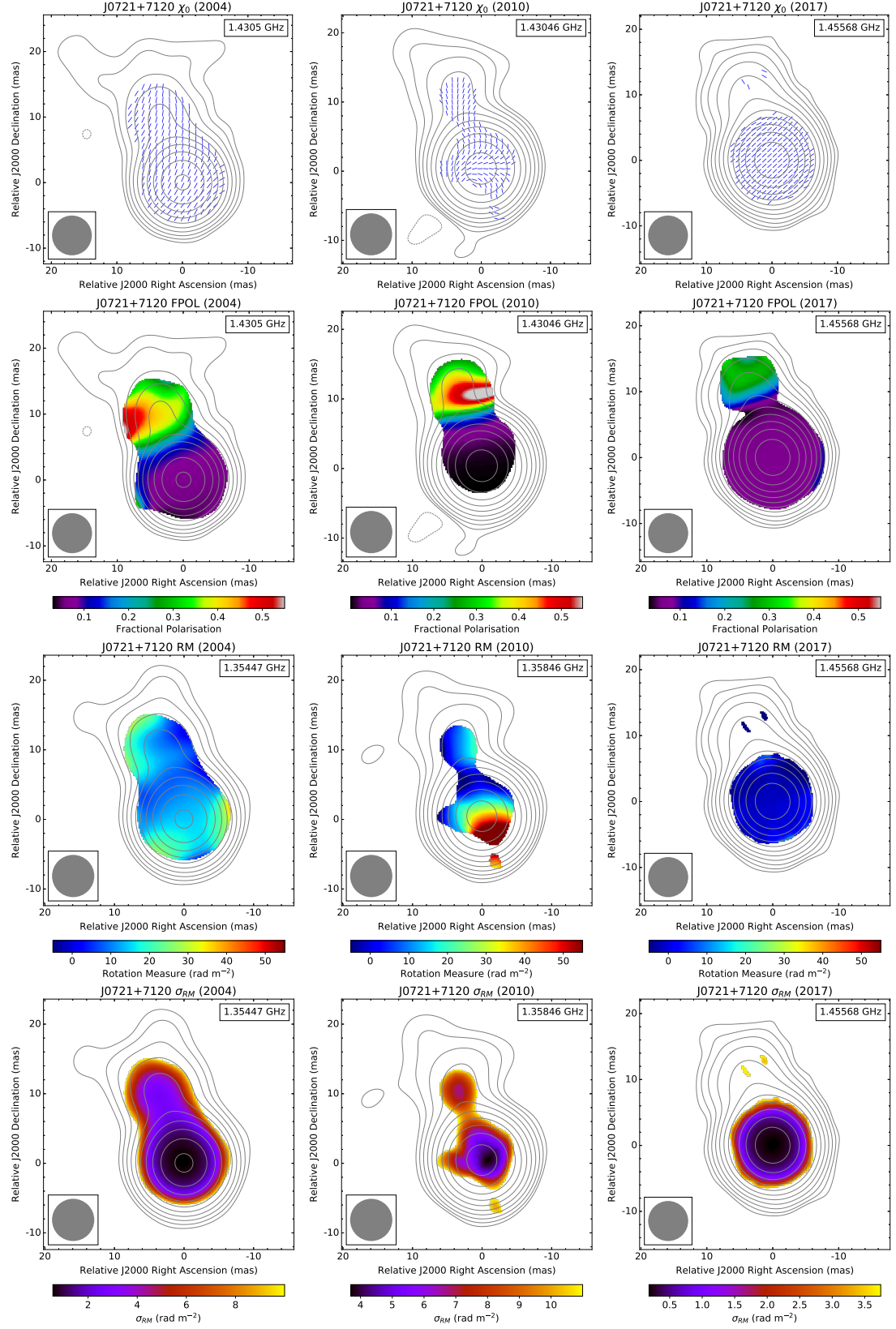


Figure 4.5: See the description of figures at the end of Section 4.1.

4.2.5 J0738+1742

The morphology of J0738+1742 has remained mostly consistent across all three epochs.

The polarisation angle structure observed in 2017 shows very similar patterns to those observed in 2004 and 2010, where the polarisation angles remain orthogonal to the jet at the edges even as the jet bends to the south. EVPAs within the core, however, are different in 2017 compared to the earlier epochs. Hallahan & Gabuzda (2008) recorded a change in polarisation angles at roughly 10 mas from the core of J0738+1742 between two observations in 1999 and 2004, with the latter being the 2004 observations considered here. This was attributed to a weakening in the longitudinal component of the magnetic field or conversely a strengthening of the transverse component.

The 2017 fractional polarisation distribution mirrors the results found in 2004 and 2010, with the percentage polarised intensity quite low in the core but almost reaching theoretical limits at the edges of the curved jet. This increase in the degree of polarisation indicates an increased magnetic field order at the edge of the jet, possibly the enhancement of an already present longitudinal field component by the curving of the jet.

No convincing systematic rotation measure gradients were identified, in either the 2004 or 2010 epochs, consistent with the 2017 observation.

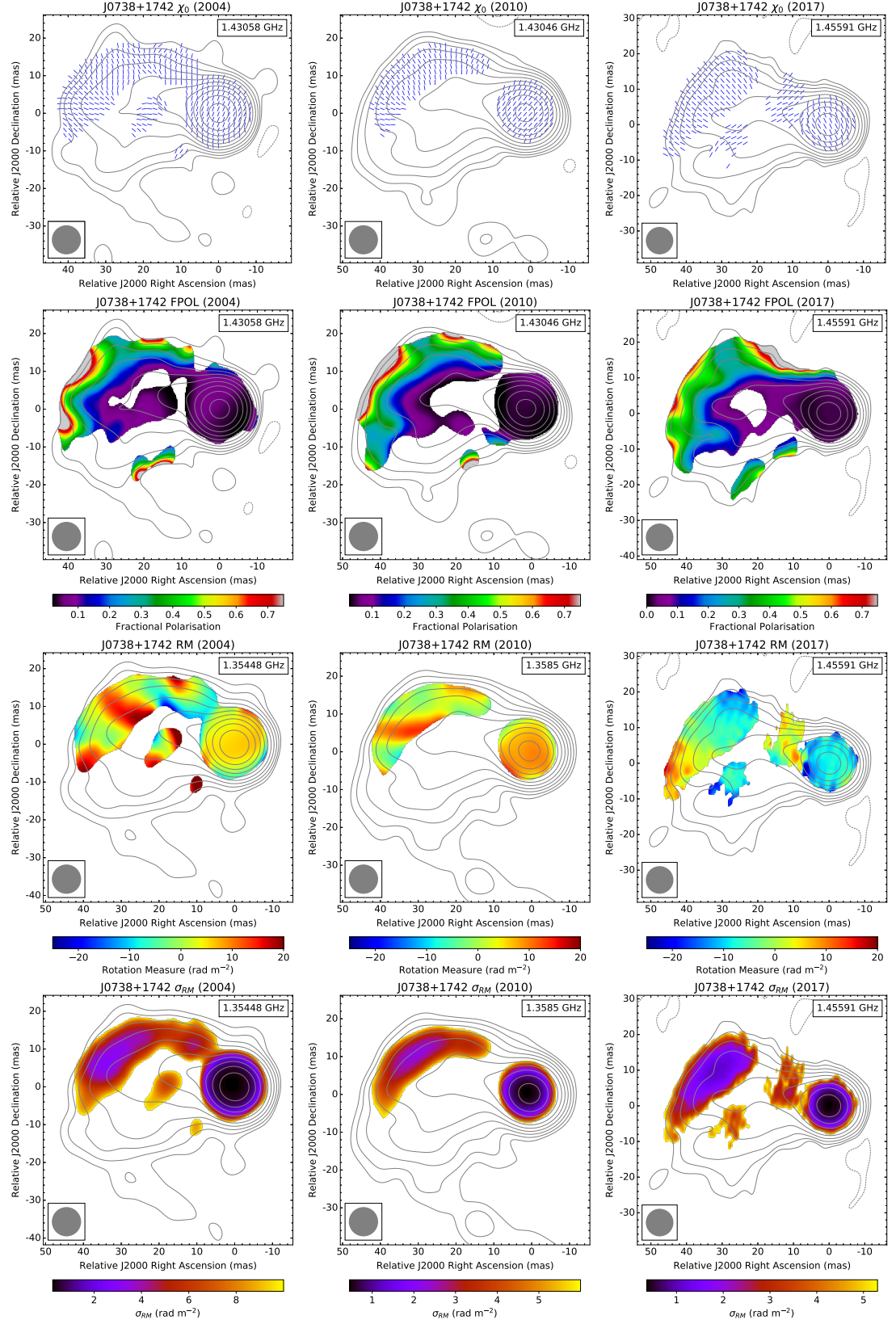


Figure 4.6: See the description of figures at the end of Section 4.1.

4.2.6 J0748+2400

The morphology of J0748+2400 has remained stable between the 2004 and 2017 observations. There were no observations made for J0748+2400 in 2010. Poor polarisation data, leading to poor fitting and noise meant only the 1.49 GHz and 1.66 GHz frequencies were suitable for use in making the rotation measure map and examining the polarisation properties. The 2004 RM map must therefore be considered tentative.

Despite these difficulties, the 2004 χ_0 map is similar to the 2017 map as well as the 15 GHz MOJAVE maps, displaying EVPAs aligned with the jet in the core but becoming orthogonal to the jet further out. Just as in the 2017 data, the fractional polarisation maps generally display a low fraction within the core, increasing outside the core, with a marked increase towards the north side. It was suggested in Chapter 3 that this is a sign of interaction with an ambient medium around the AGN or a bending helical field.

The rotation measure maps, being made using only 2 frequencies should be treated with skepticism, however, the calculated values remain similar to the 2017 observations with values mostly between 0 and 60 rad m⁻². No statistically significant gradients were found.

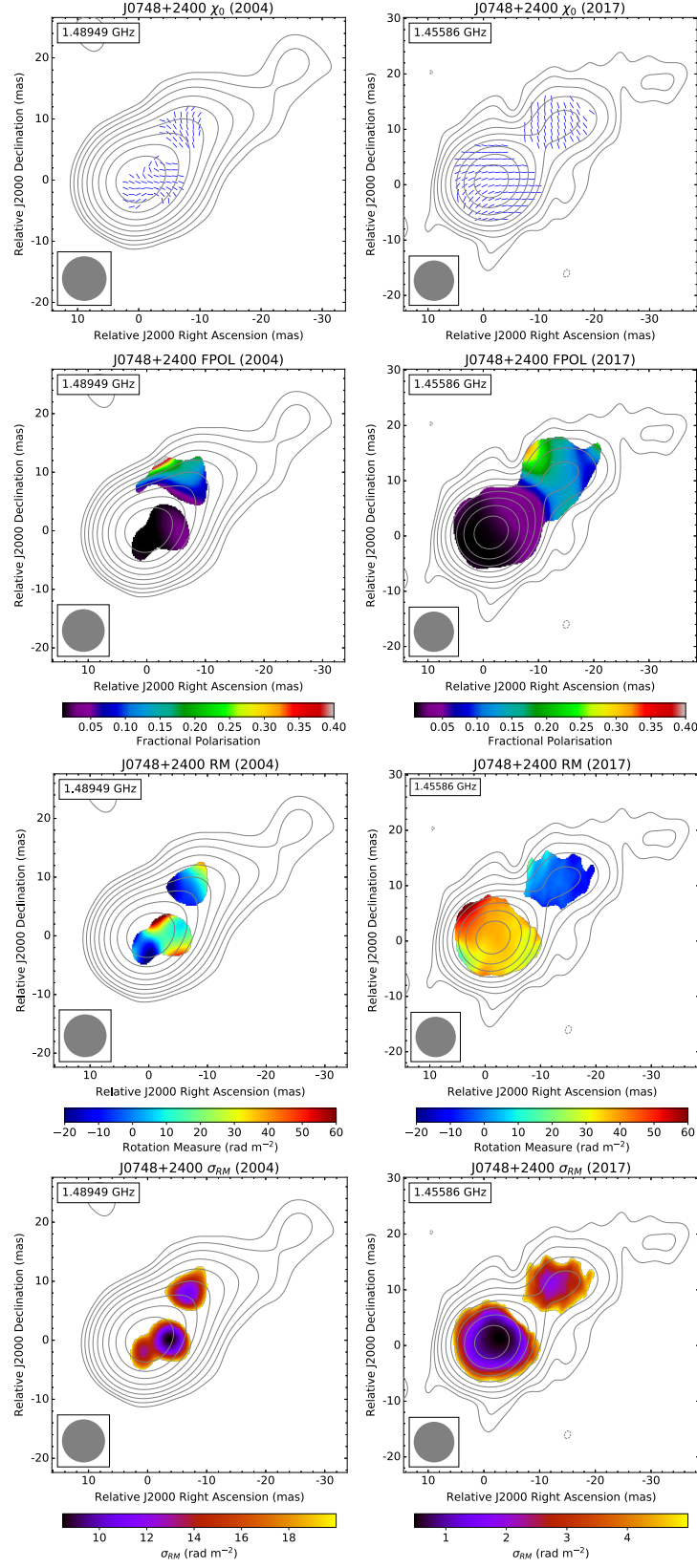


Figure 4.7: See the description of figures at the end of Section 4.1.

4.2.7 J0818+4222

The morphology of J0818+4222 is generally similar in 2010 and 2017. There were no observations made for J0818+4222 in the 2004 dataset. Less diffuse, large-scale structure appears in the 2010 image, likely due to higher noise levels.

Polarisation angle maps are shown in Figure 4.8. Poor polarisation data at 1.43 GHz and 1.49 GHz meant the 1.35 GHz data was best for comparison. Judging from the χ_0 maps, the core region has remained quite similar to that in 2017, and polarisation angles are still aligned with the jet. Similarly, the fractional polarisation structure is broadly similar, remaining lower in the core but showing a much more noticeable increase emerging from the core.

The 2010 rotation measure map shows a statistically significant transverse gradient with a significance greater than 3.5σ broadly across the entire source. This is consistent with the most notable gradient found at 5 mas east in 2017, however, no trace of the other gradient (positive to negative, north to south) from 2017, which was a reversal, was found. This could be due to the more dominant component in a nested helical magnetic field structure changing with time.

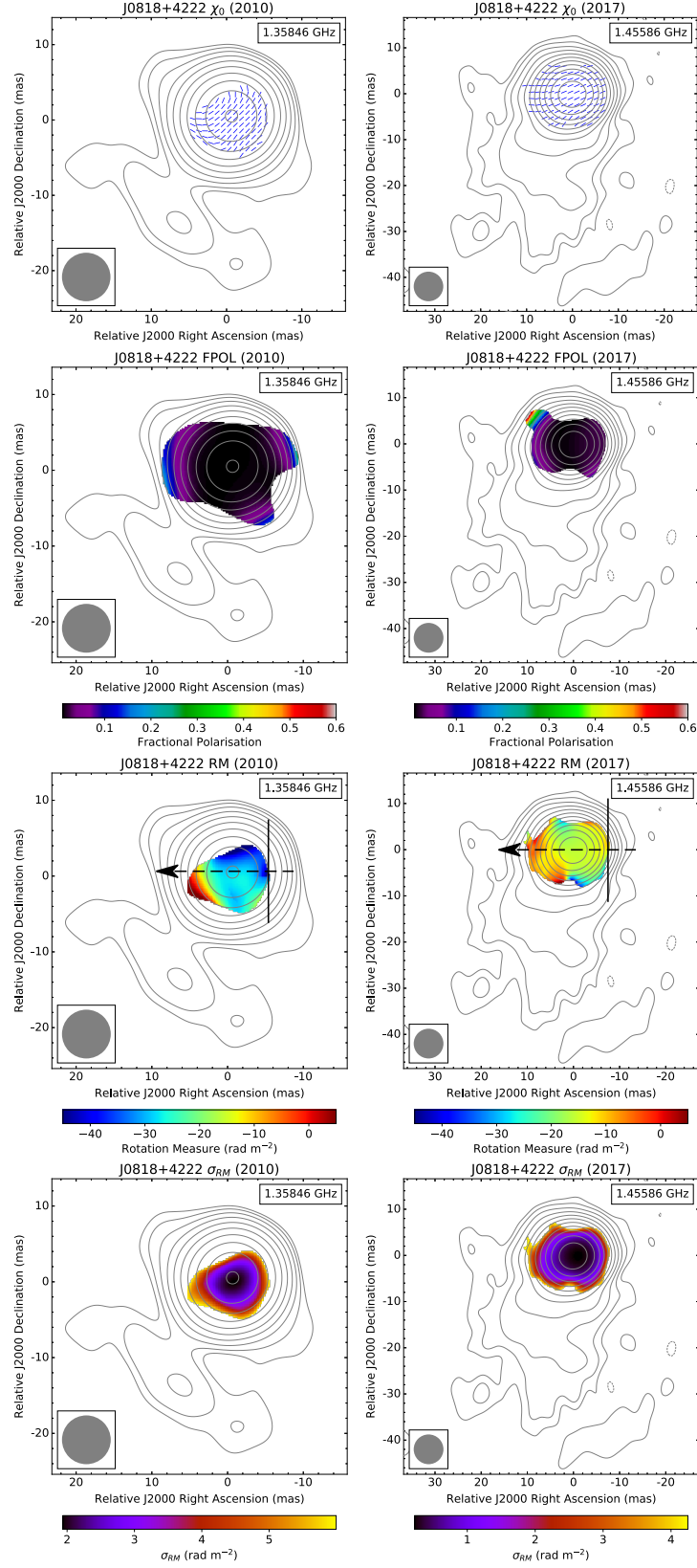


Figure 4.8: See the description of figures at the end of Section 4.1.

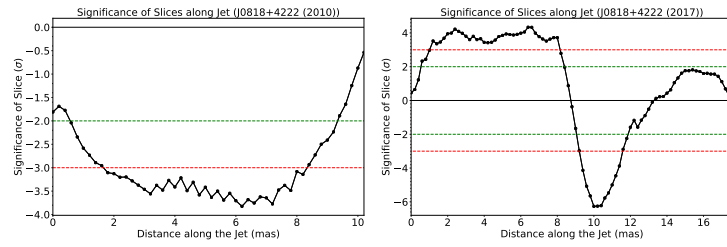


Figure 4.9: These panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrows shown in the third row of Figure 4.8. Left panel: 2010 epoch, Right panel: 2017 epoch.

4.2.8 J0825+0309

The morphology of the source J0825+0309 is broadly the same over the three epochs. The χ_0 map in 2004 shows parallel alignment of EVPAs in the inner jet, indicating an orthogonal magnetic field. The core region in 2004 and 2017 show perpendicular alignment associated with a longitudinal magnetic field. This contrasts with the core polarisation in the 2010 map which implies a dominant orthogonal field in this region.

The fractional polarisation maps are not entirely consistent over the three epochs. The 2004 map shows an increase on the eastern side of the distribution to about 25%. Little to no structure is seen in the 2010 map. The 2017 map shows an increase in fractional polarisation on the western side of the distribution. If these variations are real, they may indicate a change in the side of the jet where the interaction with the ambient medium is strongest.

The 2010 and 2017 RM maps have a broadly similar appearance, while the 2004 RM map shows a different RM distribution, with a possible transverse RM gradient over much of its length. Upon examination, as shown in Figure 4.11, the 2004 RM map only barely reaches a significance of 2σ and only for a short range of pixels. Nonetheless, this gradient is in the same direction as that reported by Gabuzda et al. (2015), based on 2, 4, and 6 cm VLBA data obtained in 1997. There are no significant transverse RM gradients in the 2010 RM map. Overall, none of these RM maps harbour strong evidence for transverse RM gradients by themselves.

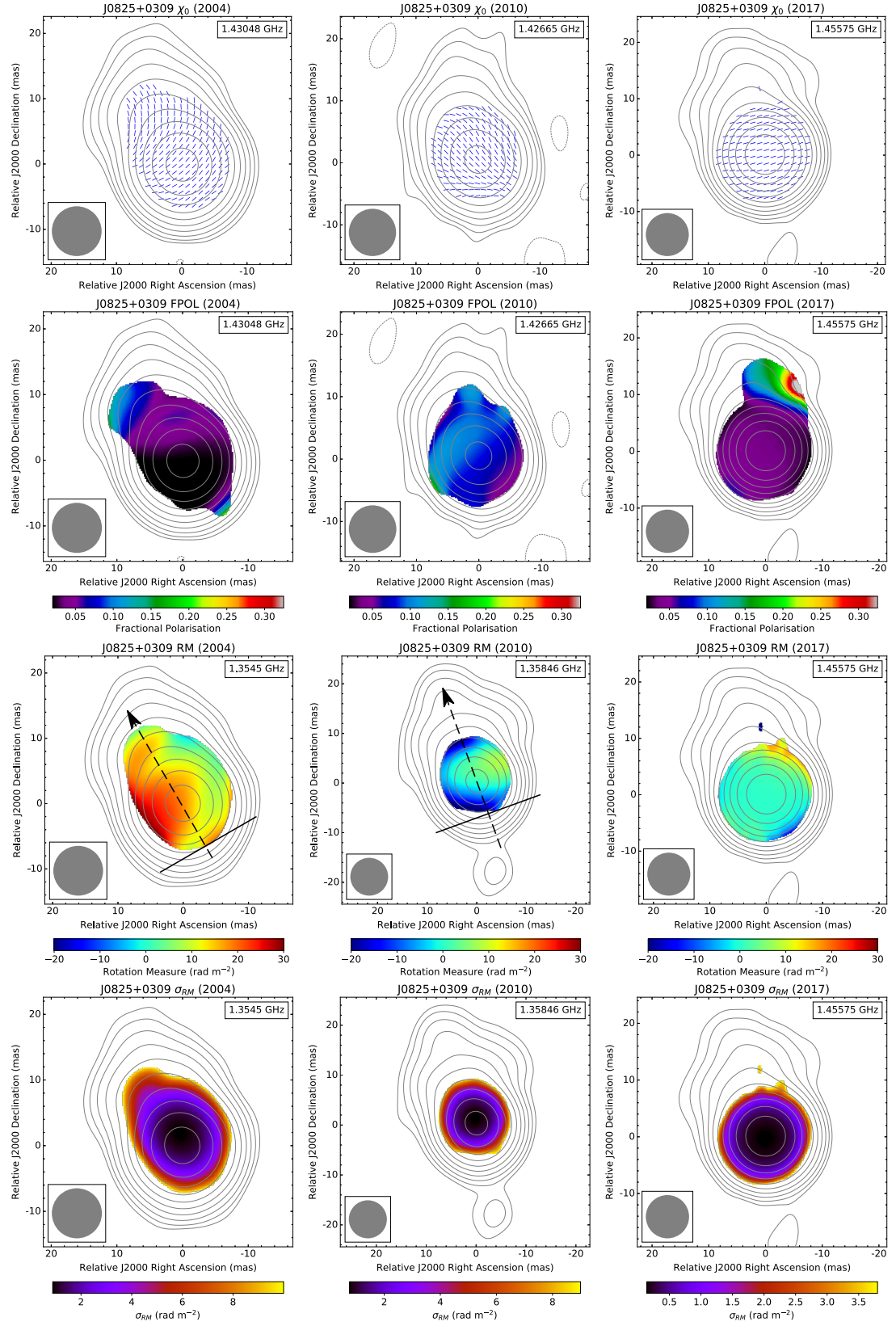


Figure 4.10: See the description of figures at the end of Section 4.1.

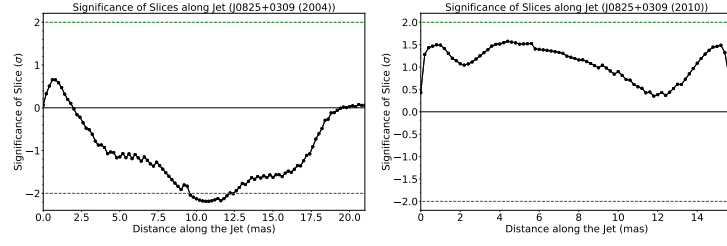


Figure 4.11: These panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrows shown in the third row of Figure 4.10. Left panel: 2004 epoch, Right panel: 2010 epoch.

4.2.9 J0854+2006

The morphology of J0854+2006 has remained similar throughout all three epochs. However, the χ_0 maps show appreciable variations in the core region.

The fractional polarisation maps remain consistent between the 2017 and 2010 maps, with 10% polarisation in the centre of the source, increasing along the jet. Interestingly the 2004 map shows hints of increases to the north of the core or innermost jet, but this increase toward the jet edges doesn't appear in the 2017 map.

The 2017 rotation measure map shows almost entirely negative values, around -20 rad m^{-2} . In contrast, the 2004 map, shows almost entirely positive values, and the 2010 map, shows a mixture of positive and negative regions of RMs.

There are no obvious monotonic transverse RM gradients in either the 2004 or the 2010 RM map. previously the 2004 data has been examined for transverse RM gradients by Motter & Gabuzda (2017) and a tentative gradient was recorded (3σ with elliptical beam and 1.8σ with the circular beam). However, this does not seem to survive when the 1.45 GHz beam was used, which puts this gradient into doubt.

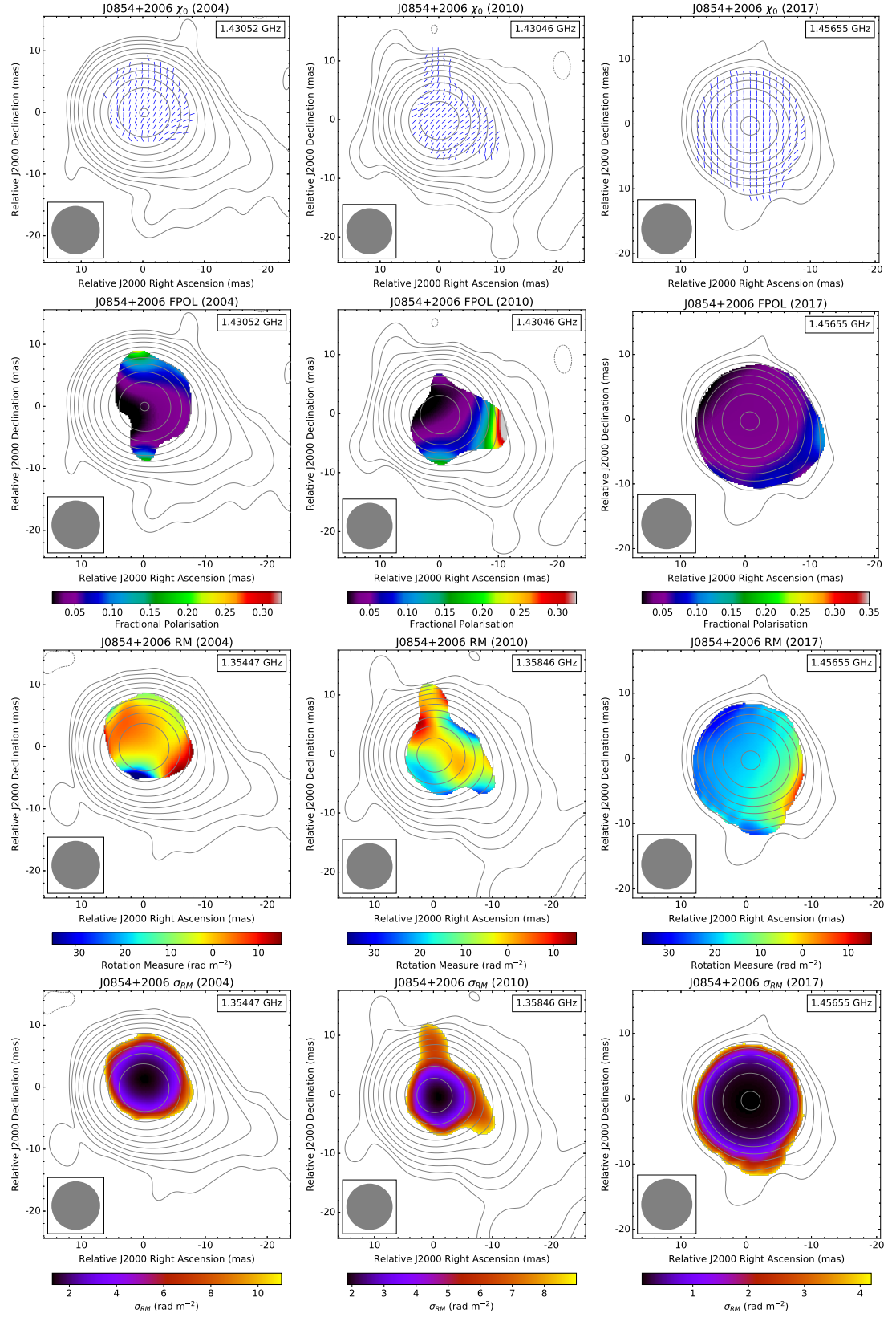


Figure 4.12: See the description of figures at the end of Section 4.1.

4.2.10 J0958+6533

The morphology of J0958+6533 has remained stable over the time between 2004 and 2017. There were no observations made for J0958+6533 in 2010. The structure of the 2004 χ_0 map seems to have changed in the core region when compared to the 2017 observations. There are the possible signs of a "spine-sheath" structure in the jet, roughly 10 mas west. Only the bottom portion of this structure was detected in 2017.

The 2004 fractional polarisation maps were predominantly below 10%. Areas of heightened polarisation intensity at roughly 5 mas west (northern edge) and 10 mas west (southern edge) are consistent with the 2017 observations. This pattern was attributed earlier to the bending of a helical field in those regions and its reappearance reinforces the idea that it is a genuine structure.

The overall core RM values are somewhat different in 2004 and 2017. As can be seen in the rotation measure map in Figure 4.13, there is the appearance of a transverse gradient as the far western side of the distribution for 2004. This was noted in Hallahan & Gabuzda (2008) but not tested for significance. Upon examination, the significance of this gradient does not exceed 2σ . Hence, it cannot be claimed to be genuine, at least using these beam parameters. There is little trace of the statistically significant RM gradients in the core that were identified in the 2017 maps.

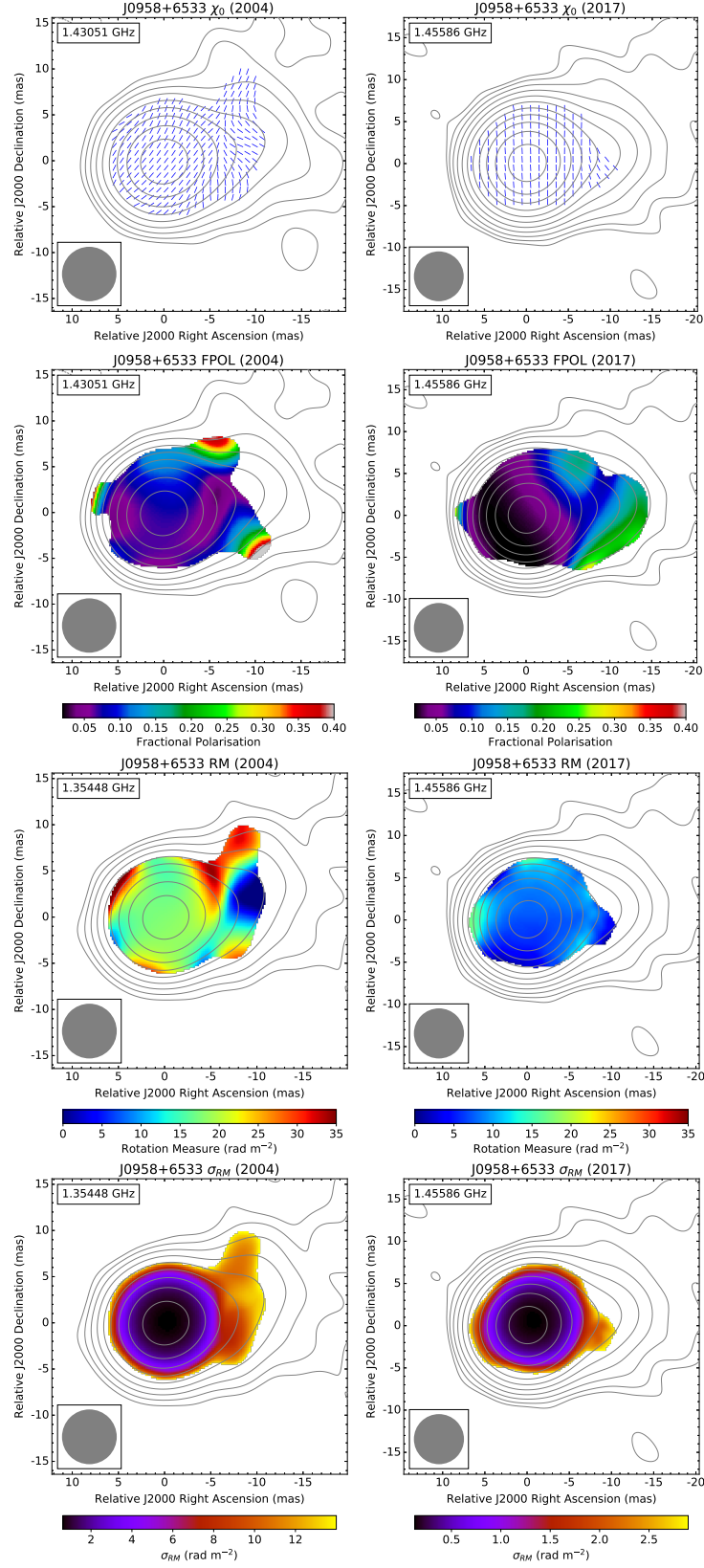


Figure 4.13: See the description of figures at the end of Section 4.1.

4.2.11 J1751+0939

The morphology of J1751+0939 has remained stable over time. The χ_0 maps for 2004 and 2019 are quite similar in the core region, corresponding to a longitudinal magnetic field. The distribution for 2010 is more complex.

The core region of the fractional polarisation maps seems consistent over time, with $m < 5\%$ for the most part. There is evidence for an increase at the western side of the jet in the 2019 map, and an increase in fractional polarisation at the eastern side in the 2010 map. If real, this may indicate changes in the side of the jet that is most strongly interacting with the ambient medium.

No evidence of a transverse rotation measure gradient was detected in either the 2004 or 2010 maps. The calculated RM values in the core region differ somewhat but lie all lie approximately within the range of 0 to 30 rad m⁻².

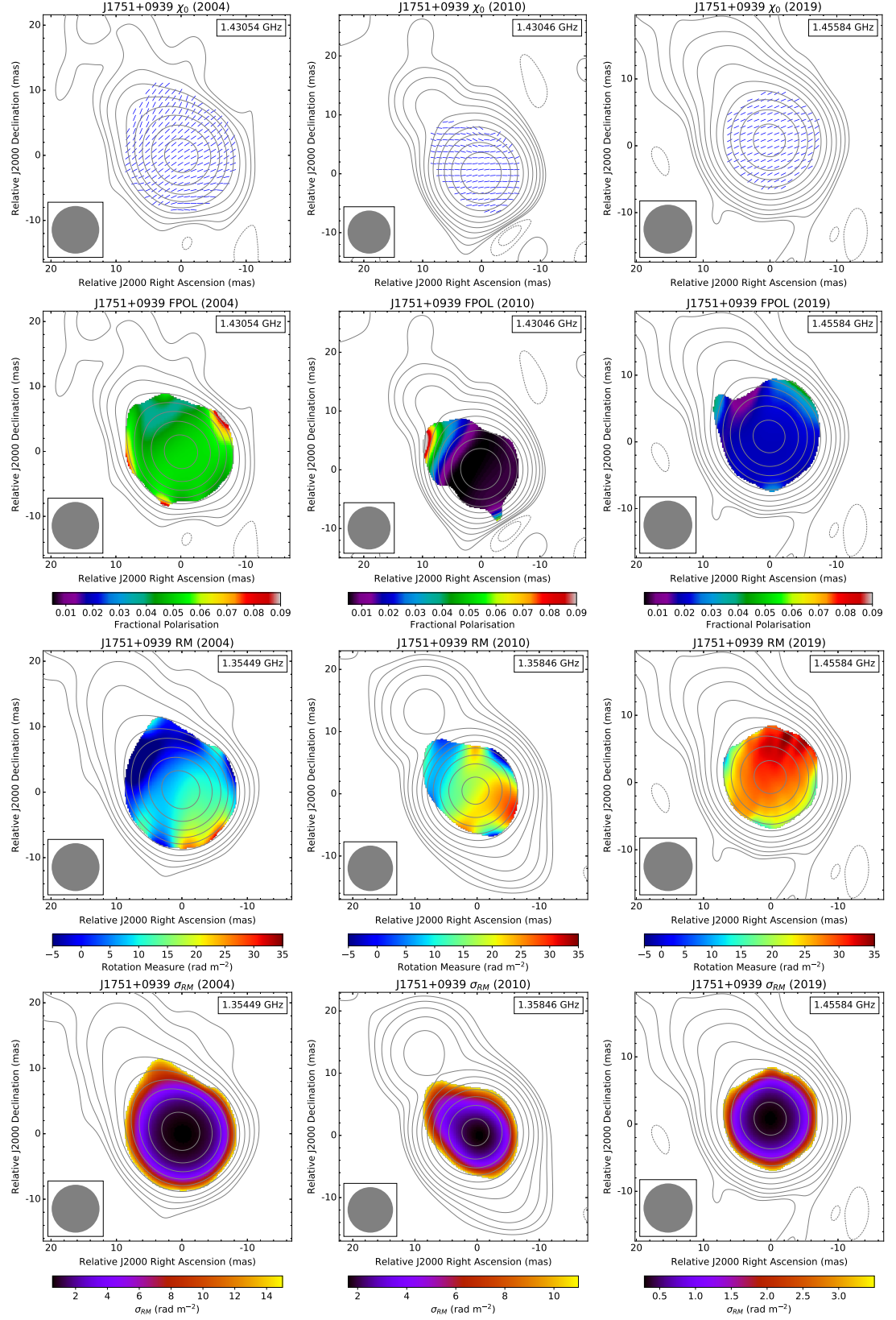


Figure 4.14: See the description of figures at the end of Section 4.1.

4.2.12 J1800+7828

The 2004 and 2010 and 2019 observations all show the jet of J1800+7828 extending to the west, before bending south. The 2004 and 2010 maps show more extensive polarisation structure in the jet than in 2019.

All the χ_0 maps show the EVPAs to be parallel to the jet along its spine, indicating an orthogonal magnetic field.

The fractional polarisation maps are fairly consistent over the three epochs. Fractional polarisation increases as usual with distance from the core region but unexpectedly, in 2004 and 2010, the fractional polarisation increases along the spine of the jet. This was suggested by Healy (2013) to be a result of turbulence at the jet edges, whereupon interaction with the ambient medium causes disorder in the magnetic field and a decrease in polarised intensity.

In the 2004 and 2010 rotation measure maps, there appears to be a checkerboard pattern in both, corresponding to a possible transverse RM gradient reversal in the core region and inner jet. As can be seen in Figure 4.16, in the 2004 map, the significance of the transverse RM gradients in both regions reach 2σ . In the 2010 RM map, only the second section, in the inner jet, shows a significance of greater than 2σ but the significance of the eastern transverse gradient is only slightly less than 2σ . None of the rotation measure maps show signs of transverse RM gradients further out in the jet. The direction of these transverse gradients differs from that of the 2019 map although the RM values overall are similar.

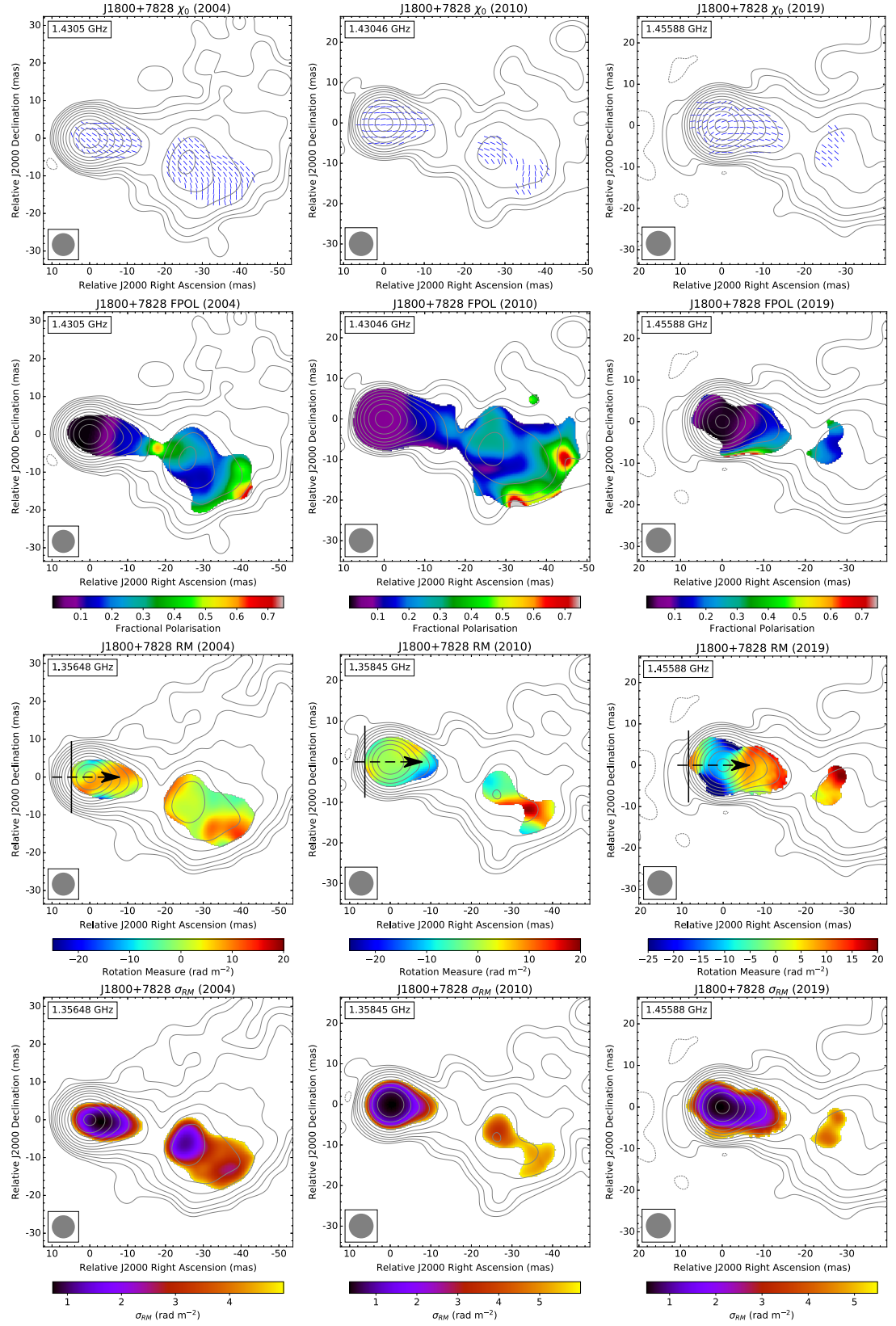


Figure 4.15: See the description of figures at the end of Section 4.1.

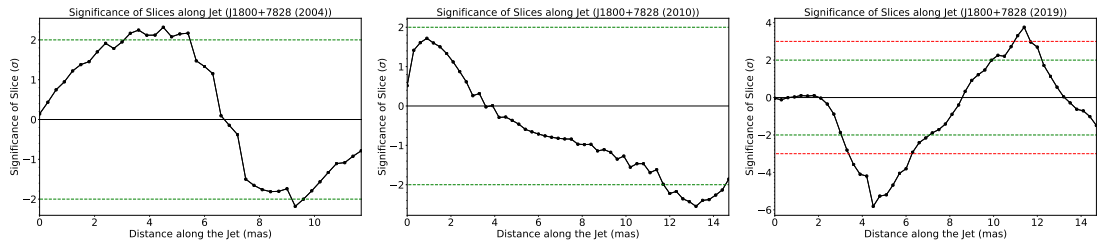


Figure 4.16: These panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrows shown in the third row of Figure 4.15. Left panel: 2004 epoch, Middle panel: 2010 epoch, Right panel: 2019 epoch.

4.2.13 J1806+6949

The morphology of J1806+6949 has remained stable over time, although the 2010 observations reveal much less of the large-scale structure seen in the 2019 data. There were no 2004 observations for J1806+6949.

As in 2019, polarisation in the core is quite low, with only a localized small patch being suitable for study. Nonetheless, in that region, the intrinsic χ_0 maps show polarisation angles being aligned with the inner jet, consistent with an orthogonal magnetic field, as in the 2019 observations. The fractional polarisation is altogether very low ($m < 3\%$) and does not seem to increase visibly towards the edges but it does increase along the jet.

There seems to be a transverse RM gradient similar to the one found in 2019, at roughly the same location down the jet. The significance involved, greater than 4σ , and the fact that it is the same direction, is good evidence that this is real. There is also evidence for a $2\text{--}3\sigma$ transverse RM gradient in the opposite direction on somewhat smaller scales in both the 2004 and 2019 RM maps. It is interesting that this weaker transverse RM gradient is in the same direction as the statistically significant gradient reported by Gabuzda et al. (2015) based on a 2+4+6 cm VLBA RM map, and it is possible that the "inner" transverse RM gradient detected in the 18–22 cm (2004) and 6–22 cm (2019) maps corresponds to the transverse RM gradient detected by Gabuzda et al. (2015).

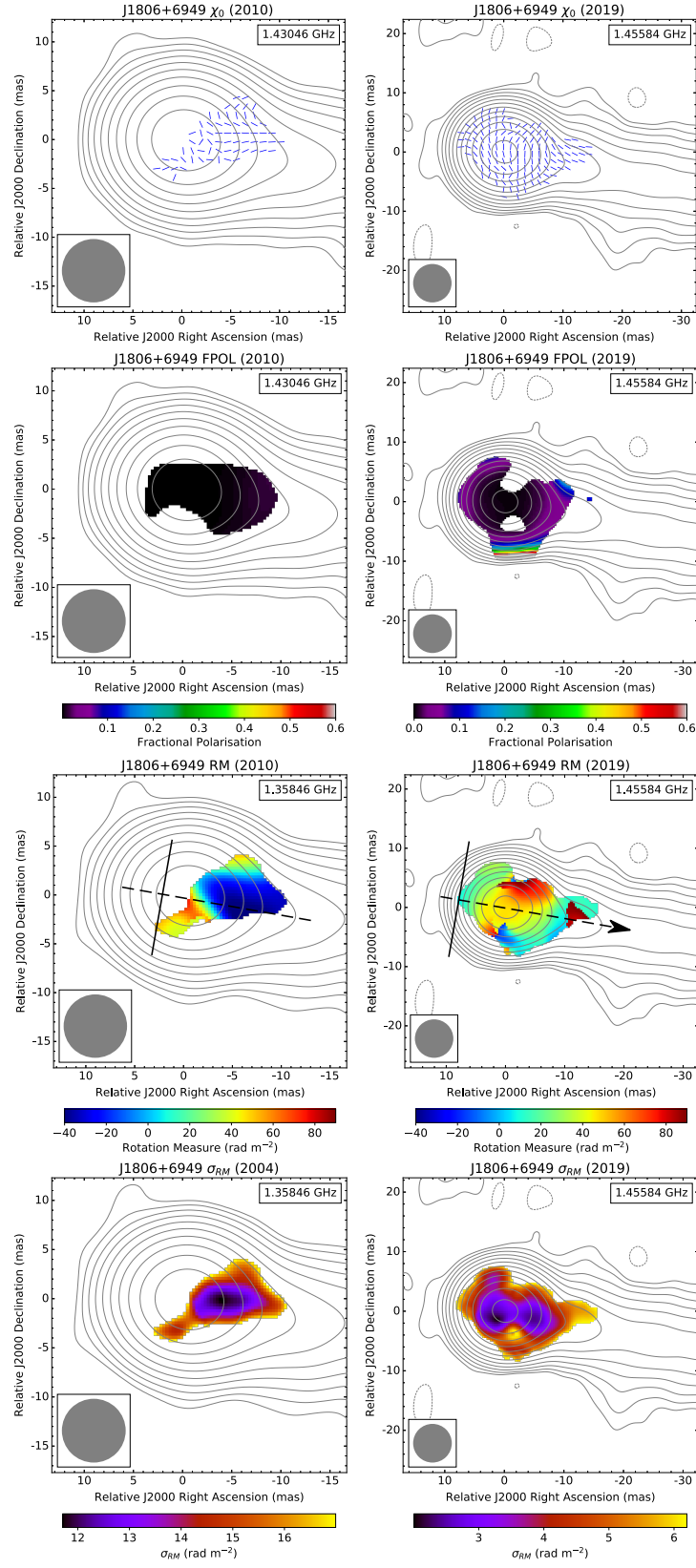


Figure 4.17: See the description of figures at the end of Section 4.1.

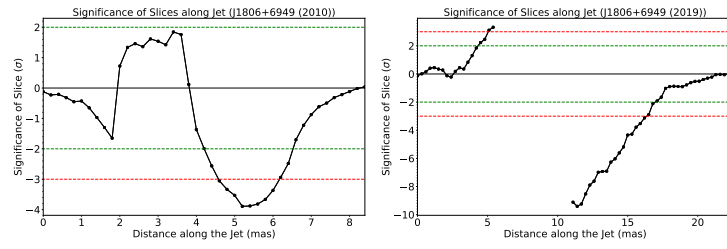


Figure 4.18: These panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrows shown in the third row of Figure 4.17. Left panel: 2010 epoch, Right panel: 2019 epoch.

4.2.14 J1824+5651

The morphology of J1824+5651 stayed the same over the three epochs. In 2004 and 2010 observations, there is much greater polarisation far out in the jet compared to 2019.

The EVPAs in the core region are very similar for all three epochs, with EVPA orientation parallel to the jet direction. Further out, in 2004 and 2010, the EVPAs are orientated perpendicular to the jet. This contrasts with the 2019 EVPAs corrected only for RM_{Gal} (See Figure 3.65) which are orientated parallel to the jet direction. This seems to indicate either that the dominant magnetic field has changed in these regions or that correcting only for RM_{Gal} was insufficient to find the true EVPA structure.

The fractional polarisation maps are all quite similar in the core region and inner jet with a rise in fractional polarisation towards the western edge of the jet. In both the 2004 and 2010 observations, the fractional polarisation is highest in the outer jet, which was not detected in 2019.

In the 2004 rotation measure map, there is little sign of any transverse gradient. An indication of a possible transverse RM gradient at a relative declination of -120 mas but its significance does not exceed 2σ . In the 2010 rotation measure maps, however, there are hints of rotation measure structure similar, but reversed, to that in the 2019 map up to a relative declination of 0 mas. The significance barely exceeds 2σ and may be the result of edge values only, so this would be considered tentative. Overall, the RM values themselves remain similar across all three epochs.

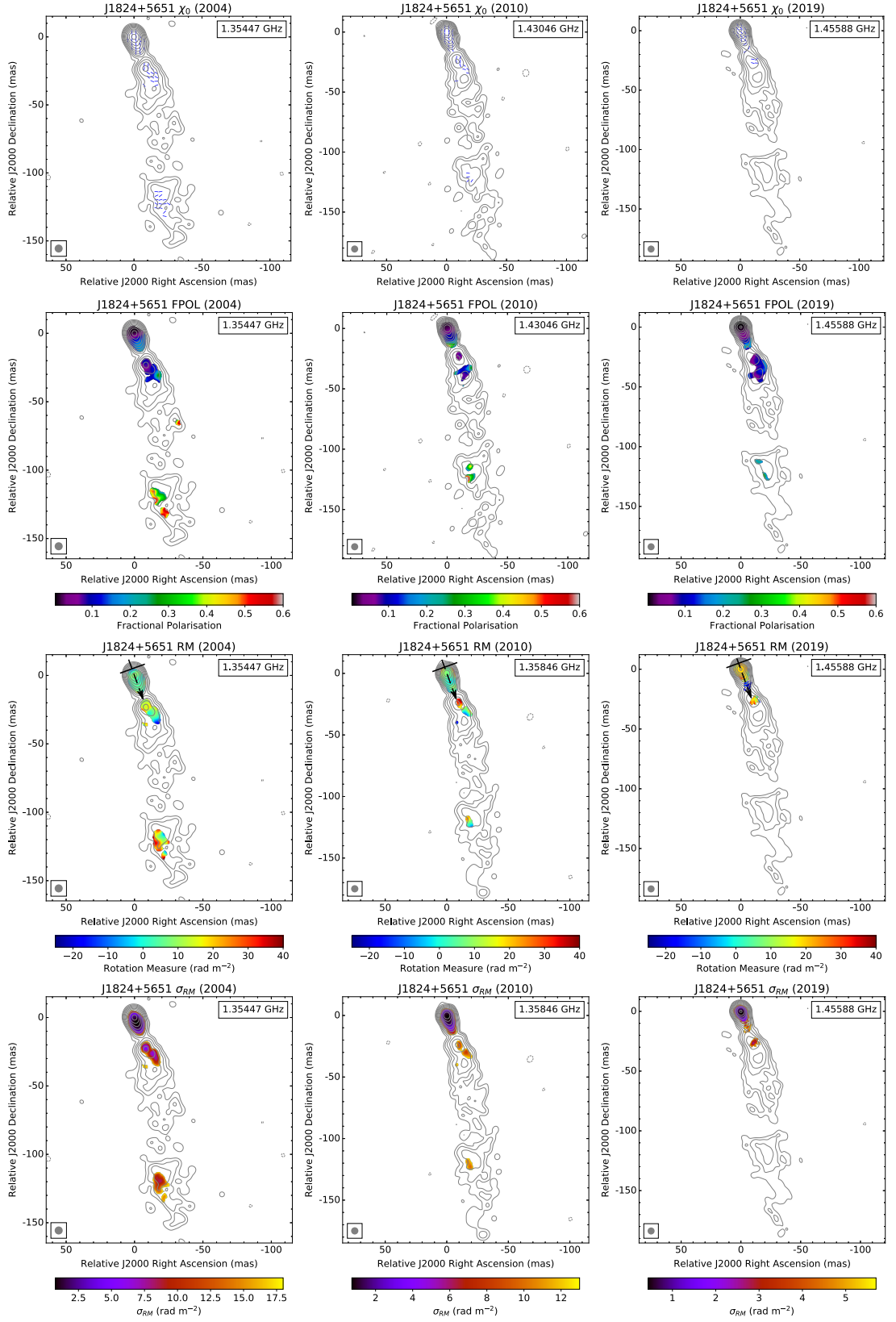


Figure 4.19: See the description of figures at the end of Section 4.1.

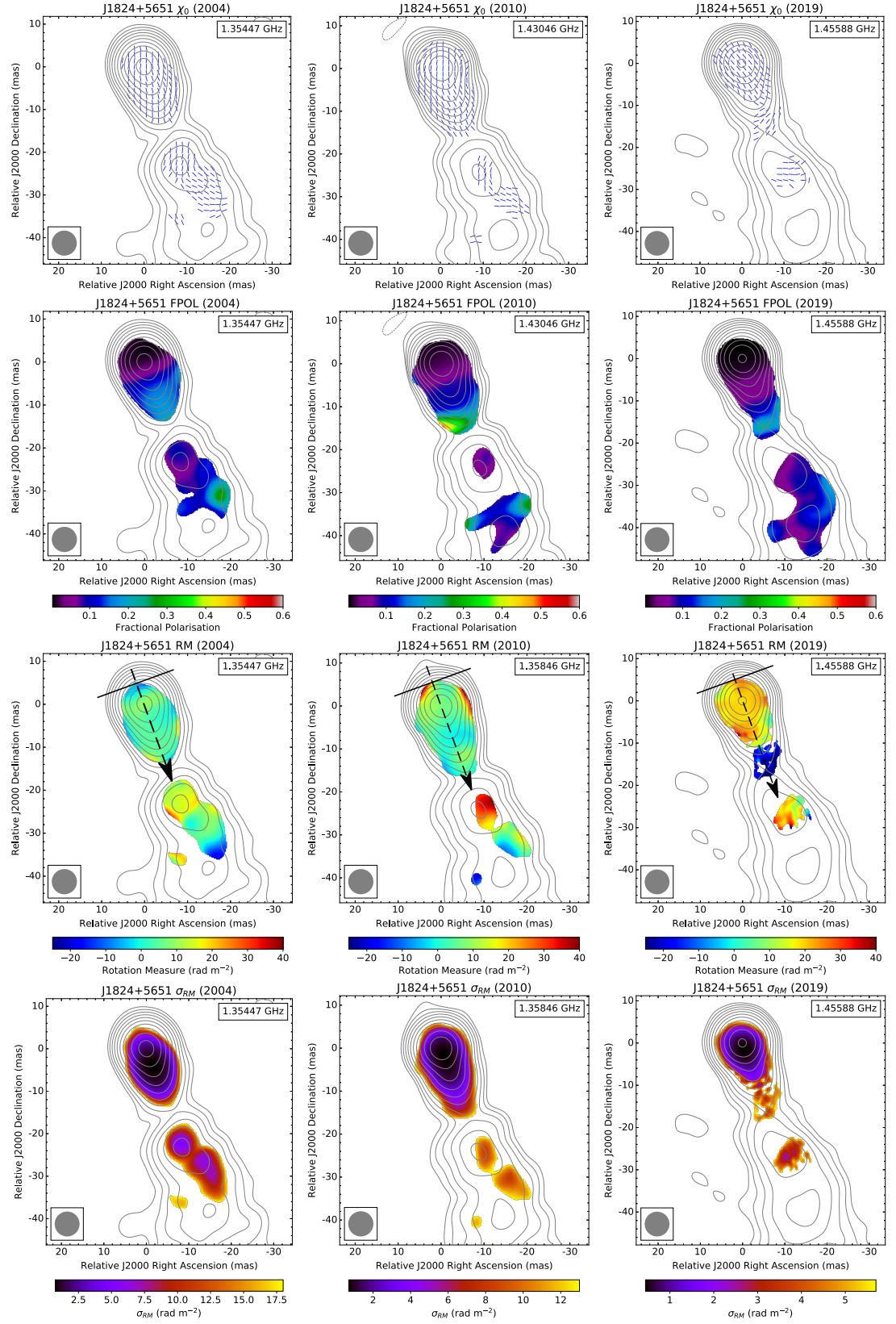


Figure 4.20: The panels in this figure are closeups of those shown in Figure 4.19, focusing on the part of the core and jet where polarisation is detected at all three epochs.

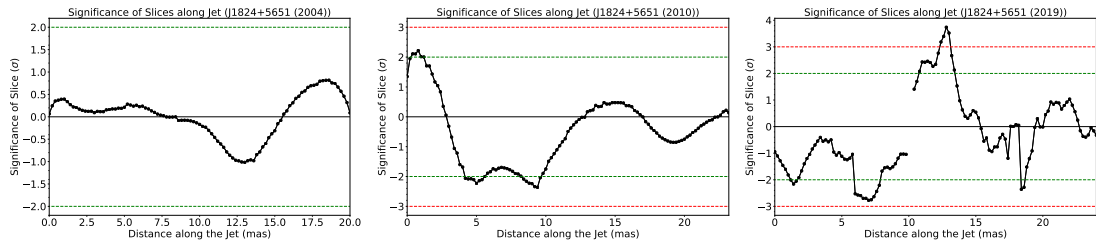


Figure 4.21: These panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrows shown in the third row of Figure 4.19. Left panel: 2004 epoch, Middle panel: 2010 epoch, Right panel: 2019 epoch.

4.2.15 J2202+4216

The morphology of the jet has stayed reasonably consistent over the three epochs. The EVPA distribution in the core region is similar across all three epochs.

Again, the fractional polarisation in the 2004 maps is very close to what was observed in 2017 and in the 1999 observations in Hallahan & Gabuzda (2008). Very little structure is visible at 2010, where polarisation was limited to the core and with degree of polarisation generally being below 15%.

No evidence of any transverse rotation measure gradients was noted in the 2004 RM map. The 2010 data was previously examined in Motter & Gabuzda (2017), who identified a transverse rotation measure gradient in the core region. This is oppositely directed to the gradient found in 2017; if both are real, this would be another example of a reversal. In the 2010 rotation measure map, there is also a region of statistically significant transverse RM gradients from a relative declination of -6 to -10 mas, although this is likely spurious, primarily due to edge pixels.

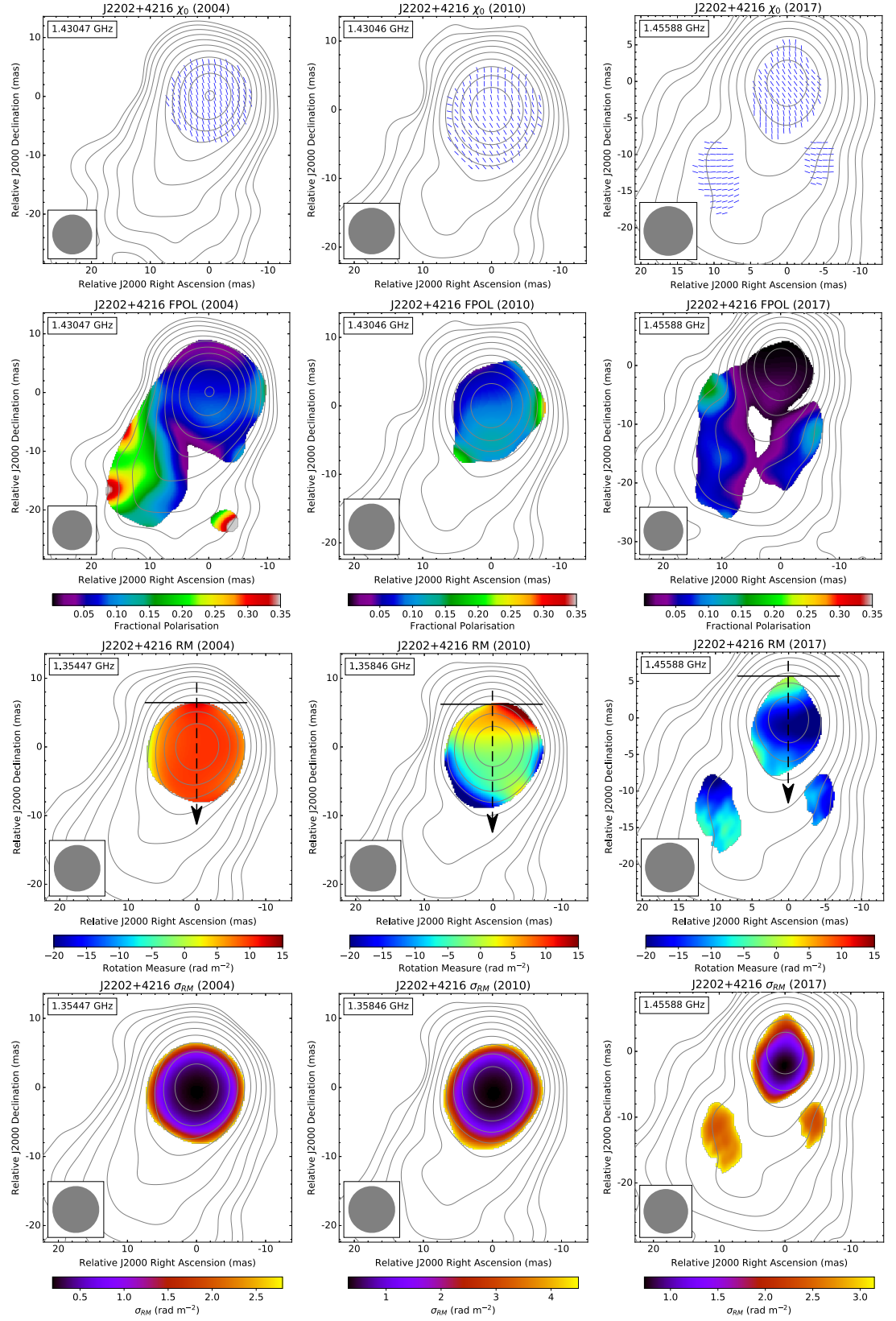


Figure 4.22: See the description of figures at the end of Section 4.1.

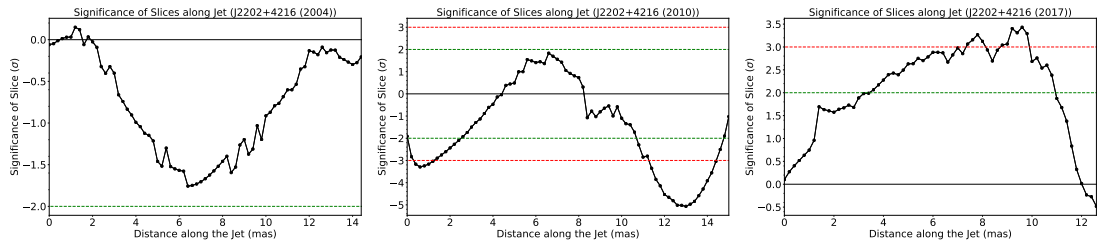


Figure 4.23: These panels plot the estimated significances of the difference of the RM values on either side of the jet, obtained using a series of slices perpendicular to the dotted arrows shown in the third row of Figure 4.22. Left panel: 2004 epoch, Middle panel: 2010 epoch, Right panel: 2017 epoch.

4.3 Summary

Of the 15 sources that were examined using previously obtained 2004 and 2010 data, the morphology of all the sources has remained stable between the three epochs, implying that these sources show little variability in intensity on decaparsec scales, as expected.

Tentative spine-sheath structures were identified in J0738+1742, J2202+4216, and J0958+6533. The first two instances were also noted in the 2017 observations, but the third was not. Apart from the core regions, which tended to be variable, the polarisation angle structure for most sources remained consistent over all three epochs.

As expected, the fractional polarisation remained low in the core region of most sources. J2202+4216 (2004) showed a fractional polarisation structure strikingly similar to that in 2017, with m increasing mainly towards the eastern edge of the jet. In several sources such as J0721+7120 and J0825+0309, the fractional polarisation distributions were significantly different at the different epochs.

Unlike the EVPA and fractional polarisation distributions, the rotation measure showed unexpected low-level but significant variability from epoch to epoch. For example, the mean RM values in the core and inner jet often differed appreciably. In some cases, transverse RM gradients remained present despite these differences in the mean RM. This has shown the parsec-to-decaparsec scale RM distribution to be much more dynamic than had previously been expected. Support for the transverse RM gradients detected in the 2017 or 2019 data was found in the earlier data for J0050-0929, J1806+6949, and J1824+5651. New evidence for RM gradient reversals was found for J0818+4222, J0825+0309, J1800+7828 and J2202+4216.

Chapter 5

Conclusions and Future Work

The first simultaneous 6, 13, 18, 21 cm VLBA polarisation observations for 16 AGN have been presented and analysed. Firstly, the polarisation angle structure, fractional polarisation, and Faraday rotation measure distribution of the sources were considered, to search for evidence of the presence of helical magnetic fields in the jets of these Active Galactic Nuclei.

Secondly, the same features were examined using older data from 2004 and 2010 at a wavelength range of 18–22 cm. Special attention was paid to whether the same features appeared again and any differences that may have occurred. Very little variation was expected between the three epochs due to the relatively large scales probed.

5.1 Evidence for Helical Fields

The following three features were examined for all 16 sources in the search for evidence for helical magnetic fields:

Polarisation Angle Structure: Of the 16 sources. Two sources (J0738+1742 and J2202+4216) showed evidence of hosting a spine-sheath structure. Seven other sources (J0721+7120, J0818+4222, J0958+6533, J1800+7828, J1806+694, J1824+5651, and J2005+7752) showed parallel alignment of EVPAs with the jet, indicative of a transverse magnetic field. Three sources (J0748+2400, J1824+5651, and possibly J0006-0623) showed regions of EVPAs aligned perpendicular to the jet, two of which also had areas of parallel alignment. Depending on the viewing angle and helical pitch angle, any of these magnetic field structures could theoretically be caused by a

helical field but we cannot be certain about this based on magnetic field structure alone.

Fractional Polarisation: Out of the 16 sources four sources (J0006-0623, J0738+1742, J0958+6533, and J2202+4216) displayed an increase in fractional polarisation towards both the jet edges. Five others (J0748+2400, J0825+0309, J1800+7828, J1824+5651, and J1806+694) showed an increase in fractional polarisation clearly on one side only, and either parallel or orthogonal EVPA alignment with the jet. All of these fractional polarisation structures could in principle be associated with a helical jet magnetic field, but this is not sufficient evidence on its own to be sure these jets carry helical magnetic fields. There were also two examples (J2202+4216 and J2005+7752) of a link between increased RM and fractional polarisation, likely caused by interaction with the intergalactic medium.

Faraday Rotation Measure: Convincing systematic monotonic rotation measure gradients with statistical significances exceeding 3σ were detected in eleven sources: J0006-0623, J0050-0929, J0121+1149, J0748+2400, J0818+4222, J0958+6533, J1800+7828, J1806+6949, J1824+5651, J2005+7752, and J2202+4216. In most cases, these transverse RM gradients have been detected for the first time. The transverse RM gradient in J0958+6533 confirms a previous report of O'Sullivan & Gabuzda (2009). Transverse RM gradients have previously been reported for J2202+4216 (Motter & Gabuzda 2017, Gómez et al. 2016). Transverse RM gradients in the opposite direction on smaller scales have been reported for J0748+2400 and J1806+6949 (Gabuzda et al. 2015), and our results may represent reversals of those gradients.

A transverse RM gradient could reflect either a toroidal magnetic field component or a gradient in the electron density across the jet. However, if there is a sign change in the RM across the jet, this can be explained only by a toroidal field component. After removing our best estimate of the Galactic RM towards the sources, three of the above sources show sign changes in the RM across their jets: J1800+7828, J1806+6949, and J2005+7752. For the other seven sources showing transverse RM gradients, a toroidal field component is the most natural explanation, but we cannot rule out the possibility that this may be due to a gradient in the thermal electron density. We also cannot rule out the possibility that the estimated Galactic RM values that have been subtracted off are not correct in some cases. We have also found reversals in the transverse RM gradients in J1800+7828 and J1824+5651, and possibly in J0818+4222 and J2005+7752 as well. This can most naturally be explained as being due to toroidal field components in a nested helical field structure, with the inner

region of helical magnetic field dominating on relatively small scales and the outer region dominating on larger scales (Mahmud et al. 2013). It would be somewhat contrived to explain such RM gradient reversals in terms of variations in the electron density.

Thus, some of these traits could be explained by phenomena other than helical magnetic fields. However, seeing multiple such signs occurring in the same source is a strong indication that a helical field is present, particularly if there is good evidence for a transverse RM gradient. A summary of possible evidence for helical magnetic fields observed in each of the 16 BL Lac objects considered here can be seen in Table 5.1. The sources showing the strongest evidence for helical jet magnetic fields are J0006-0623, J0748+2400, J0818+4222, J0958+6533, J1800+7828, J1806+6949, J1824+5651, J2005+7752, and J2202+4216.

Table 5.1: Summary of evidence for helical jet B fields.

Source	EVPA Structure	Fractional Polarisation Strucutre	Transverse RM gradient
J0006-0623	Y	Y	Y
J0050-0929	-	-	Y
J0121+1149	-	-	Y
J0721+7120	Y	Y	-
J0738+1742	Y	Y	-
J0748+2400	Y	Y	Y
J0818+4222	Y	-	Y
J0825+0309	-	Y	-
J0854+2006	-	-	-
J0958+6533	Y	Y	Y
J1751+0939	-	-	-
J1800+7828	Y	Y	Y
J1806+6949	Y	Y	Y
J1824+5651	Y	Y	Y
J2005+7752	Y	-	Y
J2202+4216	Y	Y	Y

5.2 Comparison with 2010 and 2004 Observations

The sources considered were also compared with VLBA observations obtained simultaneously at four wavelengths between 18 and 22 cm in 2004 and 2010, where available. No significant changes in morphology were detected. Outside of the core

region, which tends to be variable, no significant changes in polarisation angle structure were detected either. This implies stability on decaparsec scales for these sources. An exception would be J1824+5651 where the EVPAs changed in a feature about 25 mas south by about 90 degrees between 2010 and 2017.

Tentative spine-sheath structures were identified in two sources (J0738+1742 and J2202+4216). Both of these instances were also noticed in the 2017 observations. A number of sources showed considerably much more structure than was detected in the 2017 observations presumably due to higher noise levels in the later observations due to higher levels of interference.

Most sources showed fractional polarisation to be low in the partially optically thick core. J2202+4216 (detected in 2004 only) showed increased fractional polarisation on both sides of the jet. Four sources showed a notable increase in fractional polarisation along one side, or at a bend. Again, a number of sources show much greater structure than in 2017 or 2019. J0121+1149 in particular showed consistent orthogonal EVPAs and increased jet-edge fractional polarisation not seen in 2017. One unusual result was J1800+7828 which in both earlier epochs showed polarisation decreasing from the central spine, not clearly visible in the 2017 data.

Three sources J0818+4222, J1800+7828, and J1806+6949 shows 3σ transverse RM gradients. Of those, J0818+4222 and J1806+6949 showed the same direction as 2017 with J1800+7828 being a reversal. These results underpin those identified in 2017. Five other sources featured tentative rotation measure gradients with significance between 2 and 3σ or were non-monotonic. A transverse RM gradient detected in J0050-0929 in 2004, for example, was in the same direction as in 2017, but was not uniform and therefore less reliable. It is not surprising that more reliable transverse RM gradients were detected in the 2017/2019 data, which cover a larger range of wavelengths, corresponding to almost a factor of three in wavelength squared.

Overall the only sources that meet all the criteria expected for helical magnetic fields consistently in 2017 and at least one of the earlier epochs were J1806+6949, J1800+7828, and J2202+4216. Although the intensity and EVPA distributions were generally stable over the 10–15 years covered by these observations, the fractional polarisation and rotation measure distributions were more variable than had been expected, particularly in the core and inner jet. This shows the parsec to decaparsec scale RM distribution to be more dynamic than had been expected, possibly due to variations in the thermal electron density in the vicinity of the jet.

5.3 Future Work

Based on this thesis, there are numerous examples of work that could be done to verify the results found here, either by finding more evidence or ruling out different scenarios.

First of all, the methods and frequencies applied here could be used again to study a larger number of sources. This would extend our knowledge of the behaviour and variability of BL Lac objects as well as build more support for the existence of helical fields within their jets.

An issue plaguing many sources was uncertainty regarding the jet's direction. A detailed analysis of the proper motion studies of the sources in the sample would also be instrumental in ascertaining if the polarisation angle alignments and spine-sheath structures found within them are indeed correctly aligned with the jet.

Another more general avenue for future research involves next-generation arrays such as LOFAR in the northern hemisphere and the Square Kilometre Array (SKA) and new surveys such as the Very Large Array Sky Survey. These open up the possibility to study AGNs properties and search for transverse RM gradients on larger scales at wavelengths and with detail never previously achieved.

Finally, it would be worthwhile to revisit these same 16 sources at the same set of wavelengths used for the 2017 and 2019 observations at a future epoch. It is known that many of the sources such as BL Lac and OJ287 are highly variable, and tracking their changes at similar scales is valuable. The results of this thesis would then serve as part of ongoing work. This would be particularly relevant.

Appendices

Appendix A

Overlaying Intensity Map Parameters

The following shows the parameters for all the intensity maps in Chapter 3 and Chapter 4. This includes the peak flux, background rms, base contour level, and restoring beam parameters for intensity maps convolved with either the circular or elliptical beam. The contours in the Stokes I maps increase by either a factor of $\sqrt{2}$ (I maps on their own) or a factor of 2 (I maps superposed with other maps).

A.1 Circular Beam

Table A.1: Parameters for 2017 and 2019 intensity maps convolved with the **circular** 5 GHz (C band) beam.

Source	f (GHz)	Year	I_{peak} (Jy/beam)	Rms (mJy/beam)	Base Contour (mJy/beam)	B_{maj} (mas)	B_{min} (mas)	BPA ($^{\circ}$)
J0006-0623	4.97988	2017	2.151	0.224	1.875	2.860	2.860	0
J0050-0929	4.97988	2017	0.447	0.051	0.2	2.948	2.948	0
J0121+1149	4.97988	2017	1.293	0.297	1.25	2.683	2.683	0
J0721+7120	4.97995	2017	1.073	0.046	0.1875	2.325	2.325	0
J0738+1742	4.97991	2017	0.420	0.242	0.625	2.654	2.654	0
J0748+2400	4.97987	2017	0.449	0.155	0.5	2.583	2.583	0
J0818+4222	4.97989	2017	0.559	0.039	0.25	1.798	1.798	0
J0825+0309	4.97988	2017	1.166	0.143	0.875	2.801	2.801	0
J0854+2006	4.97984	2017	4.258	0.439	2.5	2.022	2.022	0
J0958+6533	4.97987	2017	0.678	0.069	0.5	2.180	2.180	0
J1751+0939	4.97988	2019	2.068	0.108	0.625	2.404	2.404	0
J1800+7828	4.9797	2019	1.692	0.167	1.25	3.030	3.030	0
J1806+6949	4.97989	2019	1.078	0.096	0.625	2.954	2.954	0
J1824+5651	4.97995	2019	0.695	0.135	0.5	2.078	2.078	0
J2005+7752	4.9799	2019	0.667	0.045	0.3125	2.921	2.921	0
J2202+4216	4.97992	2017	1.711	0.294	0.16875	2.473	2.473	0

Table A.2: Parameters for 2017 and 2019 intensity maps convolved with the **circular** 2.2 GHz (S band) beam.

Source	f (GHz)	Year	I_{peak} (Jy/beam)	Rms (mJy/beam)	Base Contour (mJy/beam)	B_{maj} (mas)	B_{min} (mas)	BPA ($^{\circ}$)
J0006-0623	1.45588	2017	1.017	0.306	1.75	4.919	4.919	0
J0121+1149	1.45601	2017	1.508	0.112	0.5	4.678	4.678	0
J0825+0309	1.45575	2017	1.137	0.186	1	4.761	4.761	0
J0854+2006	1.45655	2017	2.094	3.195	14.375	4.641	4.641	0
J1751+0939	1.45584	2019	0.660	0.146	0.625	4.407	4.407	0

Table A.3: Parameters for 2017 and 2019 intensity maps convolved with the **circular** 1.45 GHz (L1 band) beam.

Source	f (GHz)	Year	I_{peak} (Jy/beam)	Rms (mJy/beam)	Base Contour (mJy/beam)	B_{maj} (mas)	B_{min} (mas)	BPA ($^{\circ}$)
J0006-0623	1.45588	2017	1.350	0.301	2.25	7.742	7.742	0
J0050-0929	1.45588	2017	0.318	0.128	0.34375	7.741	7.741	0
J0121+1149	1.45601	2017	1.532	0.105	0.5	7.555	7.555	0
J0721+7120	1.45568	2017	0.536	0.114	0.3125	6.071	6.071	0
J0738+1742	1.45591	2017	0.410	0.367	1.125	7.741	7.741	0
J0748+2400	1.45586	2017	0.244	0.236	0.625	7.294	7.294	0
J0818+4222	1.45586	2017	0.589	0.110	0.34375	6.445	6.445	0
J0825+0309	1.45575	2017	1.146	0.188	1.25	7.623	7.623	0
J0854+2006	1.45655	2017	2.190	3.150	15.625	7.848	7.848	0
J0958+6533	1.45586	2017	0.650	0.125	0.4375	5.934	5.934	0
J1751+0939	1.45584	2019	0.684	0.143	0.5	7.314	7.314	0
J1800+7828	1.45588	2019	1.232	0.087	0.5	6.086	6.086	0
J1806+6949	1.45584	2019	0.649	0.054	0.25	6.492	6.492	0
J1824+5651	1.45588	2019	0.413	0.086	0.375	5.872	5.872	0
J2005+7752	1.45579	2019	0.585	0.059	0.1625	6.057	6.057	0
J2202+4216	1.45588	2017	0.934	0.190	1.1875	6.783	6.783	0

Table A.4: Parameters for 2004 intensity maps convolved with the **circular** 1.45 GHz (L1 band) beam.

Source	f (GHz)	Year	I_{peak} (Jy/beam)	Rms (mJy/beam)	Base Contour (mJy/beam)	B_{maj} (mas)	B_{min} (mas)	BPA ($^{\circ}$)
J0006-0623	1.4305	2004	1.579	0.355	1.75	7.74	7.74	0
J0006-0623	1.3545	2004	1.584	0.283	1.6875	7.74	7.74	0
J0050-0929	1.43051	2004	0.460	0.157	0.5625	7.74	7.74	0
J0050-0929	1.35448	2004	0.457	0.220	0.75	7.74	7.74	0
J0121+1149	1.4305	2004	0.887	0.368	1.125	7.55	7.55	0
J0121+1149	1.35449	2004	0.841	0.264	0.875	7.55	7.55	0
J0721+7120	1.4305	2004	0.353	0.160	0.5625	6.07	6.07	0
J0721+7120	1.35447	2004	0.327	0.142	0.625	6.07	6.07	0
J0738+1742	1.43058	2004	1.111	0.253	1.625	7.74	7.74	0
J0738+1742	1.35448	2004	1.068	0.128	1.125	7.74	7.74	0
J0748+2400	1.48949	2004	0.309	0.144	0.625	7.29	7.29	0
J0825+0309	1.43048	2004	0.935	0.291	1.375	7.62	7.62	0
J0825+0309	1.3545	2004	0.898	0.262	1.25	7.62	7.62	0
J0854+2006	1.43052	2004	1.308	0.336	1.25	7.85	7.85	0
J0854+2006	1.35447	2004	1.236	0.259	1.25	7.85	7.85	0
J0958+6533	1.43051	2004	0.301	0.263	0.75	5.93	5.93	0
J0958+6533	1.35448	2004	0.293	0.258	0.75	5.93	5.93	0
J1751+0939	1.43054	2004	0.729	0.740	2.0625	7.31	7.31	0
J1751+0939	1.35449	2004	0.662	0.281	0.875	7.31	7.31	0
J1800+7828	1.4305	2004	1.253	0.266	0.75	6.09	6.09	0
J1800+7828	1.35648	2004	1.206	0.139	0.5	6.09	6.09	0
J1824+5651	1.35447	2004	0.409	0.145	0.625	5.87	5.87	0
J2202+4216	1.43047	2004	1.656	0.459	1.5625	6.78	6.78	0
J2202+4216	1.35447	2004	1.640	0.281	1.875	6.78	6.78	0

Table A.5: Parameters for 2010 intensity maps convolved with the **circular** 1.45 GHz (L1 band) beam.

Source	f (GHz)	Year	I_{peak} (Jy/beam)	Rms (mJy/beam)	Base Contour (mJy/beam)	B_{maj} (mas)	B_{min} (mas)	BPA ($^{\circ}$)
J0006-0623	1.43046	2010	1.398	0.517	2.5	7.74	7.74	0
J0006-0623	1.35846	2010	1.291	0.352	2.5	7.74	7.74	0
J0050-0929	1.43048	2010	0.328	0.290	1.125	7.74	7.74	0
J0050-0929	1.35846	2010	0.304	0.295	1.25	7.74	7.74	0
J0121+1149	1.43046	2010	0.906	0.255	0.875	7.55	7.55	0
J0121+1149	1.35846	2010	0.800	0.252	0.625	7.55	7.55	0
J0721+7120	1.43046	2010	0.350	0.134	0.46875	6.07	6.07	0
J0721+7120	1.35846	2010	0.317	0.099	0.4375	6.07	6.07	0
J0738+1742	1.43046	2010	0.747	0.187	1.125	7.74	7.74	0
J0738+1742	1.3585	2010	0.746	0.217	1.0625	7.74	7.74	0
J0818+4222	1.35846	2010	1.503	0.986	3.125	6.44	6.44	0
J0825+0309	1.42665	2010	0.827	1.282	2.625	7.62	7.62	0
J0825+0309	1.35846	2010	0.770	0.220	1.1875	7.62	7.62	0
J0854+2006	1.43046	2010	1.027	0.296	1.25	7.85	7.85	0
J0854+2006	1.35846	2010	0.927	0.254	1.25	7.85	7.85	0
J1751+0939	1.43046	2010	1.291	0.329	1.375	7.31	7.31	0
J1751+0939	1.35846	2010	1.141	0.301	0.875	7.31	7.31	0
J1800+7828	1.43046	2010	1.149	0.251	1.625	6.09	6.09	0
J1800+7828	1.35845	2010	1.016	0.248	1	6.09	6.09	0
J1806+6949	1.43046	2010	1.085	0.312	1.125	6.49	6.49	0
J1806+6949	1.35846	2010	0.950	0.282	1	6.49	6.49	0
J1824+5651	1.43046	2010	0.824	0.219	0.875	5.87	5.87	0
J1824+5651	1.35846	2010	0.738	0.203	0.875	5.87	5.87	0
J2202+4216	1.43046	2010	2.150	0.435	2.5	6.78	6.78	0
J2202+4216	1.35846	2010	1.969	0.328	2.5	6.78	6.78	0

A.2 Elliptical Beam

Table A.6: Parameters for 2017 and 2019 intensity maps convolved with the **elliptical** 5 GHz (C band) beam.

Source	f (GHz)	Year	I_{peak} (Jy/beam)	Rms (mJy/beam)	Base Contour (mJy/beam)	B_{maj} (mas)	B_{min} (mas)	BPA ($^{\circ}$)
J0006-0623	4.97988	2017	2.176	0.234	1.875	4.700	1.737	-1.52
J0050-0929	4.97988	2017	0.449	0.062	0.225	4.907	1.772	-2.7
J0121+1149	4.97988	2017	1.456	0.189	1.25	4.021	1.789	-1.55
J0721+7120	4.97995	2017	1.082	0.051	0.2	2.966	1.820	-4.53
J0738+1742	4.97991	2017	0.384	0.096	0.28125	3.846	1.827	-3.04
J0748+2400	4.97987	2017	0.439	0.122	0.5	3.548	1.885	-3.74
J0818+4222	4.97989	2017	0.534	0.069	0.28125	2.428	1.331	-8.06
J0825+0309	4.97988	2017	1.170	0.111	0.875	4.243	1.850	0.42
J0854+2006	4.97984	2017	4.151	0.904	3.75	2.924	1.402	-4.94
J0958+6533	4.97987	2017	0.684	0.101	0.625	2.645	1.796	-0.72
J1751+0939	4.97988	2019	2.081	0.123	0.625	3.483	1.663	1.91
J1800+7828	4.9797	2019	1.680	0.161	1.25	3.210	2.861	-1.06
J1806+6949	4.97989	2019	1.075	0.095	0.625	3.154	2.765	29.16
J1824+5651	4.97995	2019	0.700	0.129	0.5	2.259	1.914	16.11
J2005+7752	4.9799	2019	0.669	0.058	0.3125	3.080	2.769	45.67
J2202+4216	4.97992	2017	1.758	0.317	0.16875	3.361	1.823	-7.57

Table A.7: Parameters for 2017 and 2019 intensity maps convolved with the **elliptical** 2.2 GHz (S band) beam.

Source	f (GHz)	Year	I_{peak} (Jy/beam)	Rms (mJy/beam)	Base Contour (mJy/beam)	B_{maj} (mas)	B_{min} (mas)	BPA ($^{\circ}$)
J0006-0623	1.45588	2017	0.676	0.333	2.25	8.400	2.880	-2.47
J0121+1149	1.45601	2017	1.523	0.093	0.625	7.520	2.910	-3.18
J0825+0309	1.45575	2017	1.137	0.168	1	7.790	2.910	-3.35
J0854+2006	1.45655	2017	2.029	3.024	16.875	7.180	3.000	-7.75
J1751+0939	1.45584	2019	0.659	0.143	0.625	6.960	2.790	-7.3

Table A.8: Parameters for 2017 and 2019 intensity maps convolved with the **elliptical** 1.45 GHz (L1 band) beam.

Source	f (GHz)	Year	I_{peak} (Jy/beam)	Rms (mJy/beam)	Base Contour (mJy/beam)	B_{maj} (mas)	B_{min} (mas)	BPA ($^{\circ}$)
J0006-0623	1.45588	2017	1.027	0.319	2.25	12.890	4.650	-2.72
J0050-0929	1.45588	2017	0.319	0.131	0.375	13.230	4.530	-4.39
J0121+1149	1.45601	2017	1.548	0.130	0.5	11.720	4.870	-1.93
J0721+7120	1.45568	2017	0.541	0.121	0.3125	7.810	4.720	-6.47
J0738+1742	1.45591	2017	0.378	0.337	1.03125	12.080	4.960	-7.73
J0748+2400	1.45586	2017	0.237	0.228	0.625	10.020	5.310	-3.43
J0818+4222	1.45586	2017	0.571	0.110	0.34375	8.340	4.980	-9.22
J0825+0309	1.45575	2017	1.147	0.174	1	12.030	4.830	-4.34
J0854+2006	1.45655	2017	2.147	2.674	13.125	11.060	5.810	-2.72
J0958+6533	1.45586	2017	0.646	0.126	0.4375	7.070	4.980	-2.51
J1751+0939	1.45584	2019	0.686	0.142	0.5	11.030	4.850	-3.57
J1800+7828	1.45588	2019	1.226	0.152	0.5	6.420	5.770	5.82
J1806+6949	1.45584	2019	0.642	0.048	0.25	6.820	6.180	-18.07
J1824+5651	1.45588	2019	0.414	0.091	0.375	6.180	5.580	-1.22
J2005+7752	1.45579	2019	0.584	0.059	0.1625	6.250	5.870	36.71
J2202+4216	1.45588	2017	0.980	0.203	1.1875	9.370	4.910	-10.61

Appendix B

Sigma Plots for Unreliable Gradients

The following figures plot the estimated significances of the difference of the RM values on either side of the jet from Chapter 3. These results were not shown in the main part of the thesis as they were deemed to be spurious, or unreliable. Although they formally show regions where the formal significance of the difference of the RM values on either side of the jet reaches or exceeds 3σ , further examination showed that the progression of RM values across the jet was not monotonic, or the large difference between the edge RM values was due primarily to a jump at one edge of the jet. This shows the importance of checking for reasonable monotonicity and uniformity of the RM slices across the jet.

B.1 J0738+1742

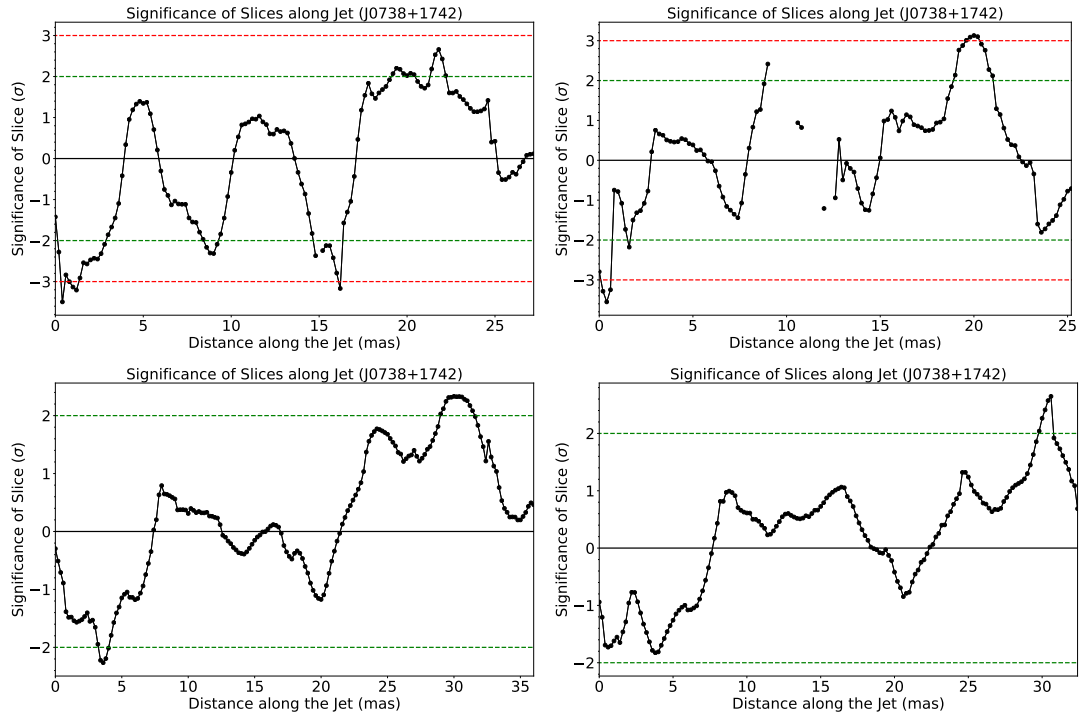


Figure B.1: These panels plot the estimated significances of the difference of the RM values on either side of the jet of J0738+1742 (1.45 GHz beam), obtained using a series of slices perpendicular to the dotted arrows shown in the top two panels of Figure 3.26. The top two panels of this figure are core region and inner jet. The bottom two panels are the jet after bending, from a relative right ascension of 20 to 50 mas. The reason this result was deemed to be unreliable: apparently significant transverse gradients only occur over regions of a few pixels, are not uniform and convolution with a circular or elliptical beam gives inconsistent results. Also, the RM distribution is mostly quite patchy.

B.2 J0825+0309

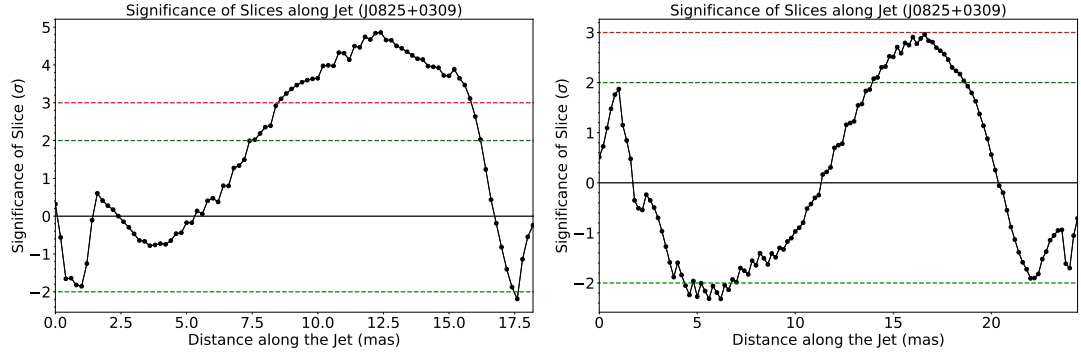


Figure B.2: These panels plot the estimated significances of the difference of the RM values on either side of the jet of J0825+0309 (1.45 GHz beam), obtained using a series of slices perpendicular to the dotted arrow shown in the top two panels of Figure 3.38. The reason this result was deemed to be unreliable: apparently significant transverse gradients due mainly to small number of pixels along one edge and are not uniform.

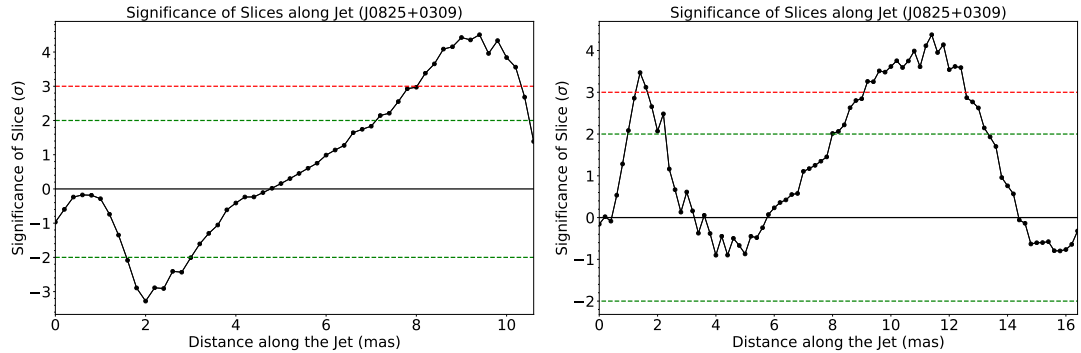


Figure B.3: These panels plot the estimated significances of the difference of the RM values on either side of the jet of J0825+0309 (2.2 GHz beam), obtained using a series of slices perpendicular to the dotted arrow shown in the top two panels of Figure 3.39. The reason this result was deemed to be unreliable: apparently significant transverse gradients due mainly to small number of pixels along one edge and are not uniform.

B.3 J0854+2006

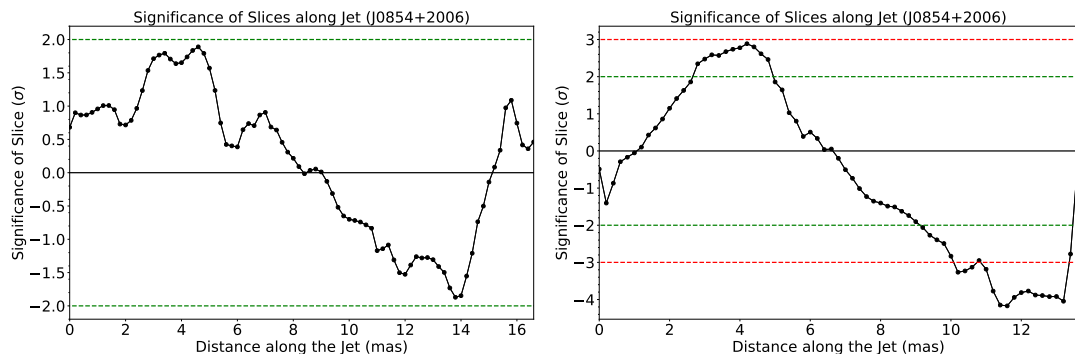


Figure B.4: These panels plot the estimated significances of the difference of the RM values on either side of the jet of J0854+2006 (1.45 GHz beam), obtained using a series of slices perpendicular to the dotted arrow shown in the top two panels of Figure 3.43. The reason this result was deemed to be unreliable: apparently significant transverse gradients due mainly to small number of pixels along one edge, are not uniform and are only detected with convolution with an elliptical beam.

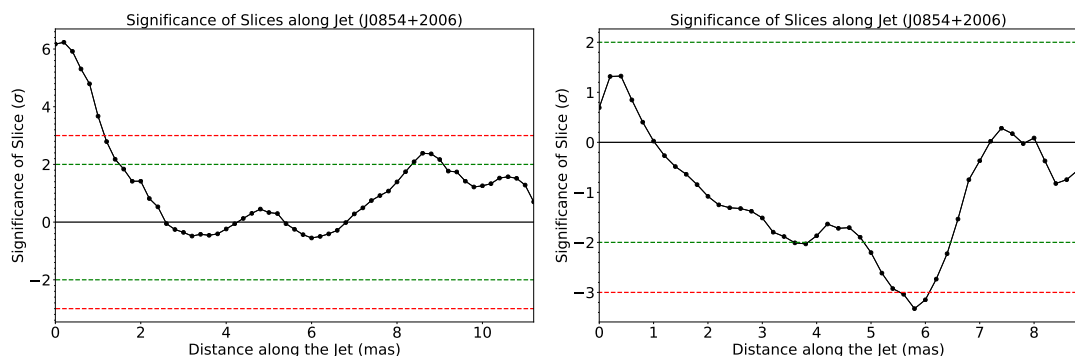


Figure B.5: These panels plot the estimated significances of the difference of the RM values on either side of the jet of J0854+2006 (2.2 GHz beam), obtained using a series of slices perpendicular to the dotted arrow shown in the top two panels of Figure 3.44. The reason this result was deemed to be unreliable: apparently significant transverse gradients due mainly to small number of pixels along one edge, are not uniform and results are inconsistent with corresponding 1.45 GHz beam plots.

B.4 J1751+0939

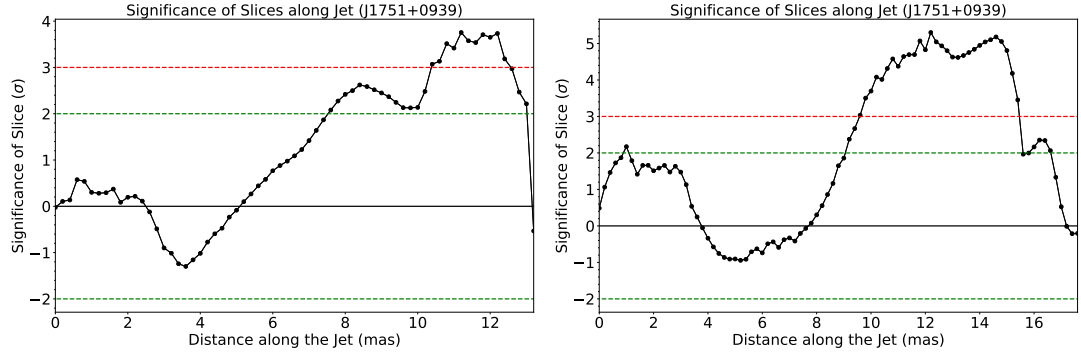


Figure B.6: These panels plot the estimated significances of the difference of the RM values on either side of the jet of J1751+0939 (1.45 GHz beam), obtained using a series of slices perpendicular to the dotted arrow shown in the top two panels of Figure 3.53. The reason this result was deemed to be unreliable: apparently significant transverse gradients due are due mainly to a small number of pixels along one edge and are not uniform.

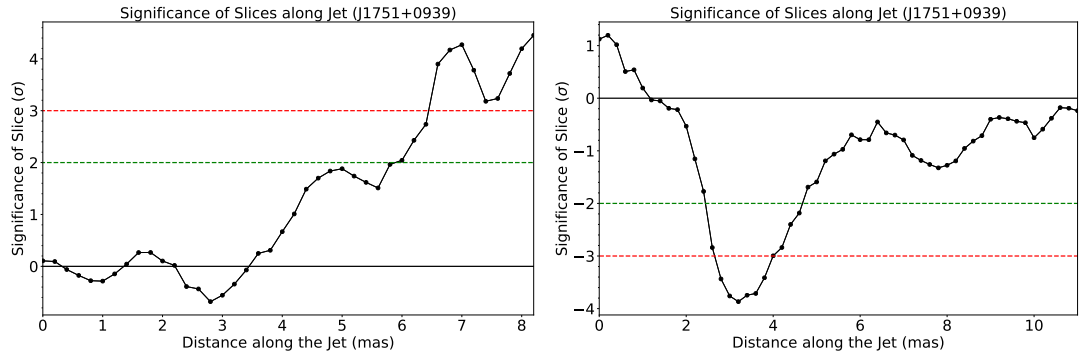


Figure B.7: These panels plot the estimated significances of the difference of the RM values on either side of the jet of J1751+0939 (2.2 GHz beam), obtained using a series of slices perpendicular to the dotted arrow shown in the top two panels of Figure 3.54. The reason this result was deemed to be unreliable: apparently significant transverse gradients are not monotonic, convolution with a circular (left) or elliptical (right) beam gives inconsistent results and results are inconsistent with corresponding 1.45 GHz beam plots.

Appendix C

Slice Plots

The following depicts representative typical transverse slices across the jet for each of the sources in Chapter 3. These plots illustrate how monotonic and uniform a particular RM gradient is, and help distinguish between a genuine statistically significant gradient and one merely caused by extreme values along one edge of the jet.

C.1 L1 Beam

C.1.1 J0006-0623

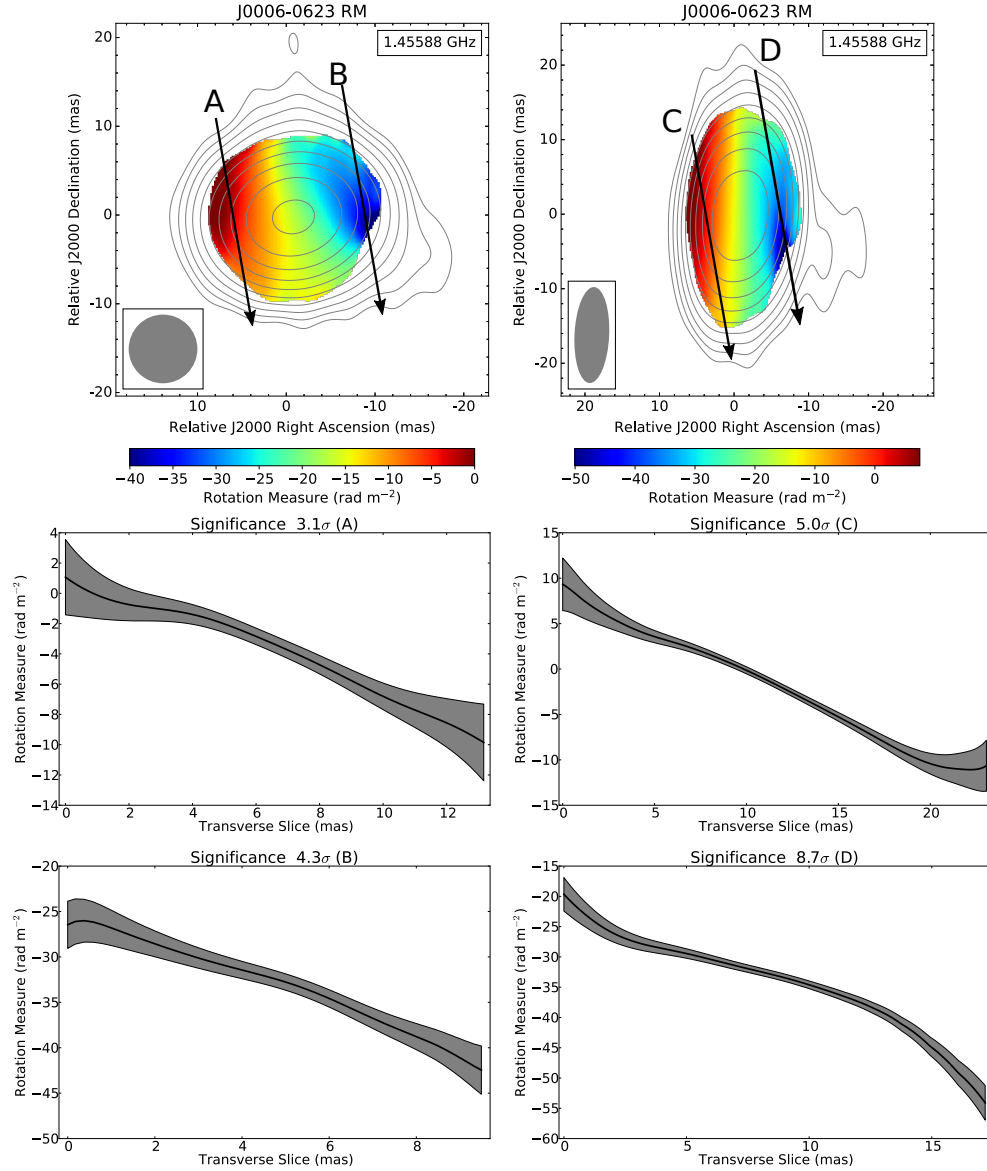


Figure C.1: It can be seen that the elliptical beam has distorted the orientation of the RM gradient along the jet out from the core, and the statistical significances given by the slices across the map made with the circular beam are more reliable. The corresponding slices for the maps made with the 2.2 GHz beam are shown in Appendix C.2

C.1.2 J0050-0929

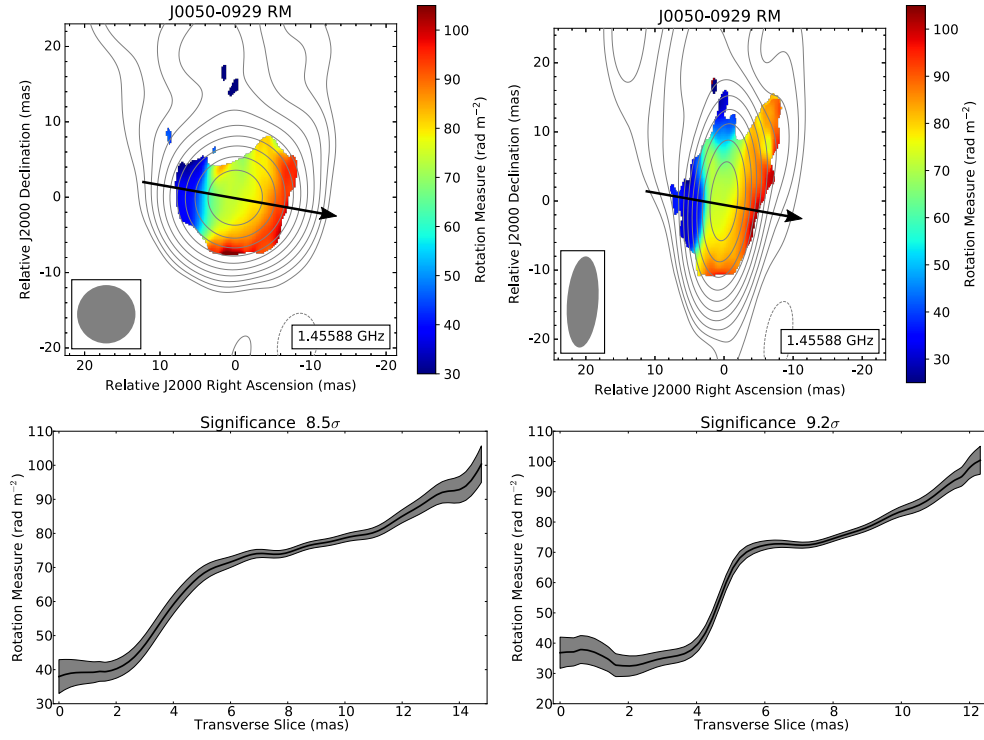


Figure C.2: Although these slices are not uniform, they are monotonic. Even the part of the slice to the right of the jump has a significance exceeding 3σ .

C.1.3 J0121+1149

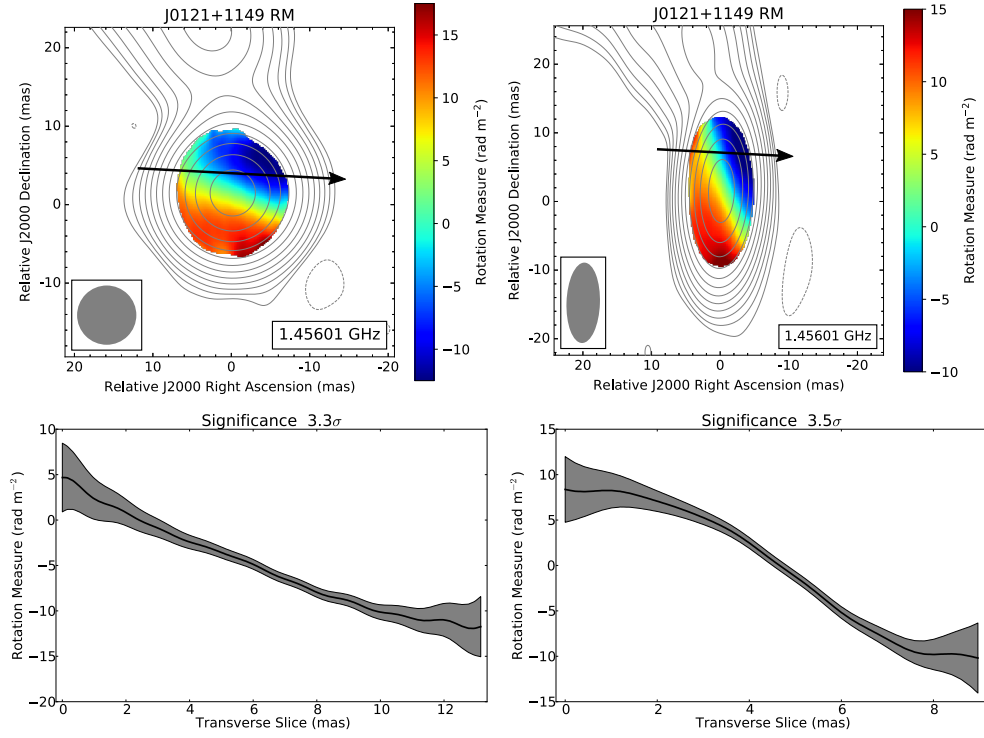
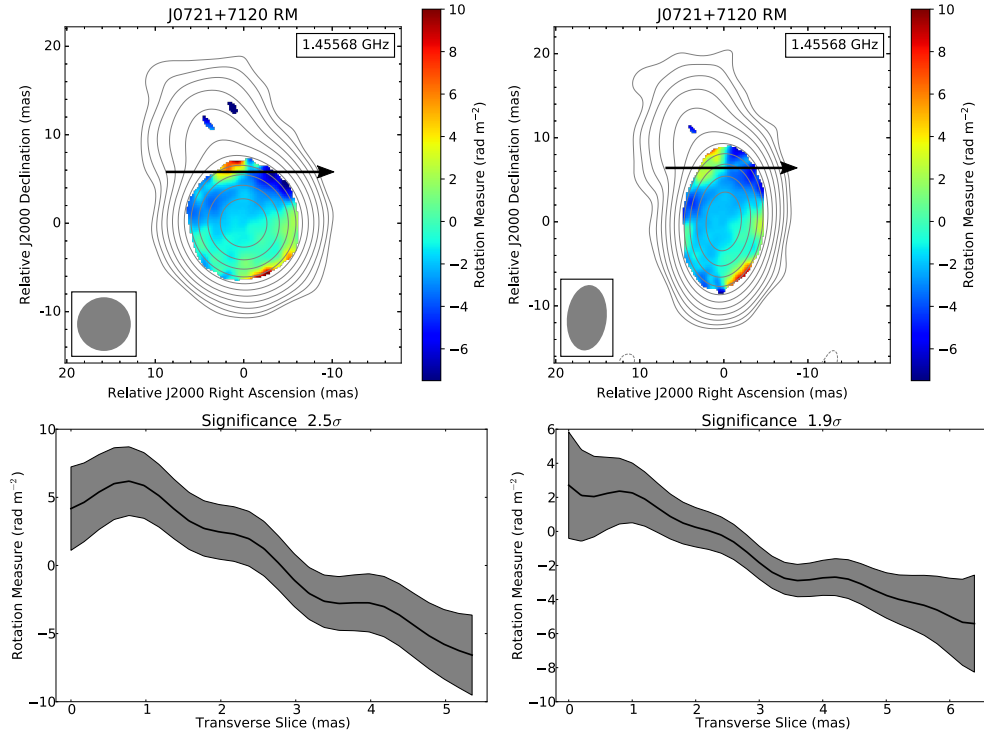
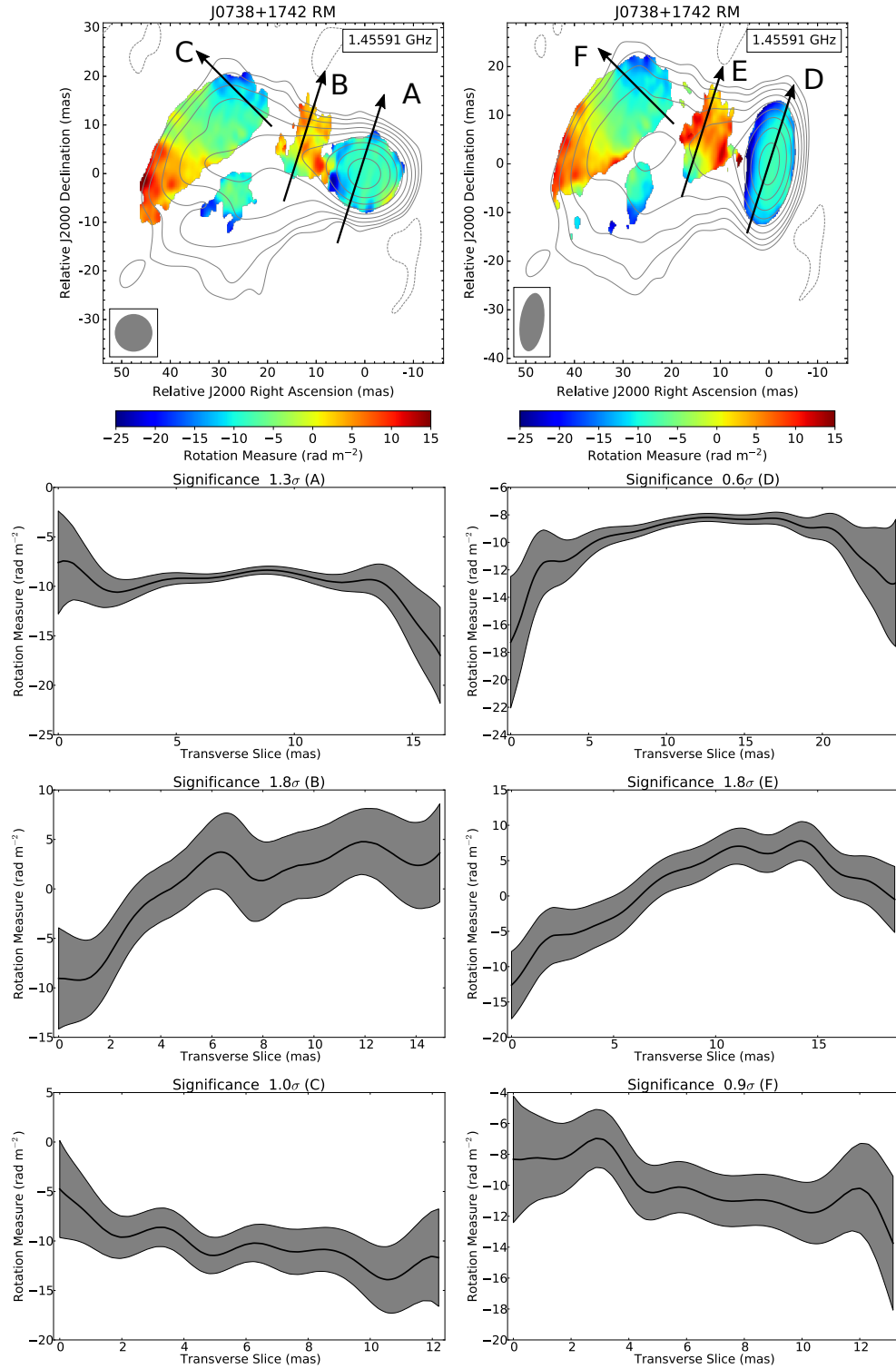


Figure C.3: The corresponding slices for the maps made with the 2.2 GHz beam are shown in Appendix C.2.

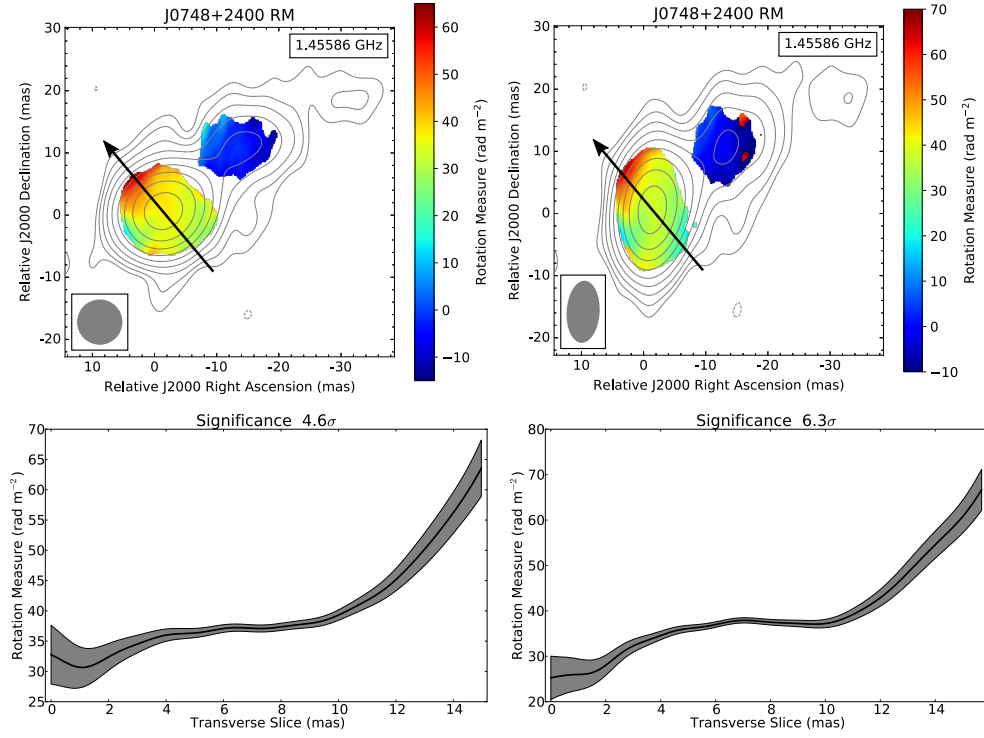
C.1.4 J0721+7120



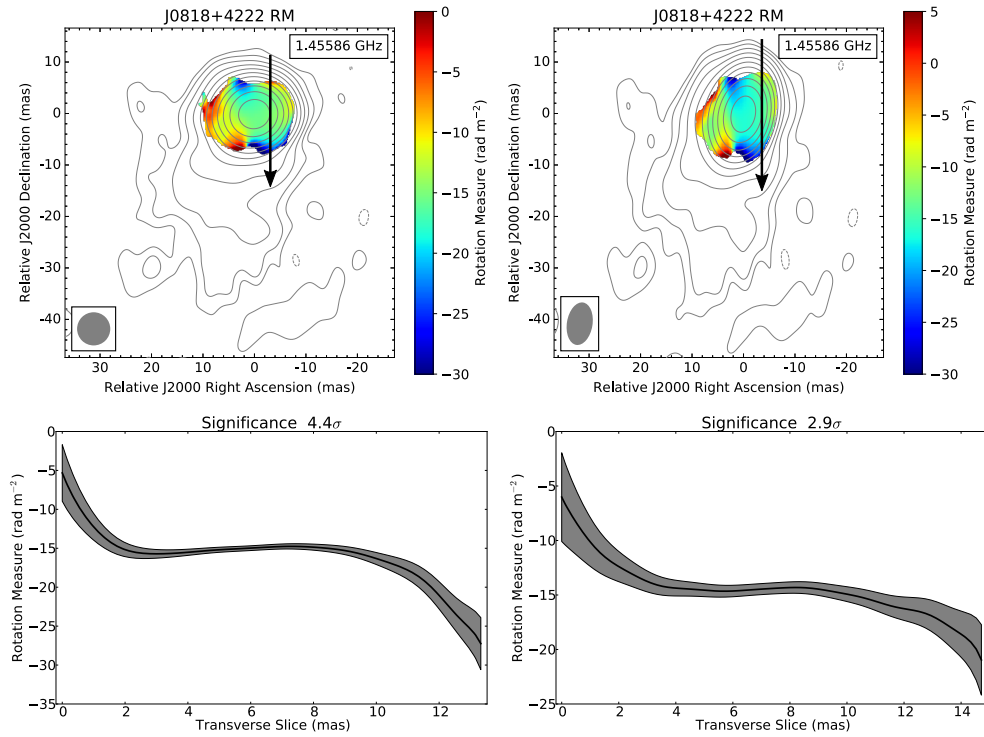
C.1.5 J0738+1742



C.1.6 J0748+2400



C.1.7 J0818+4222



C.1.8 J0825+0309

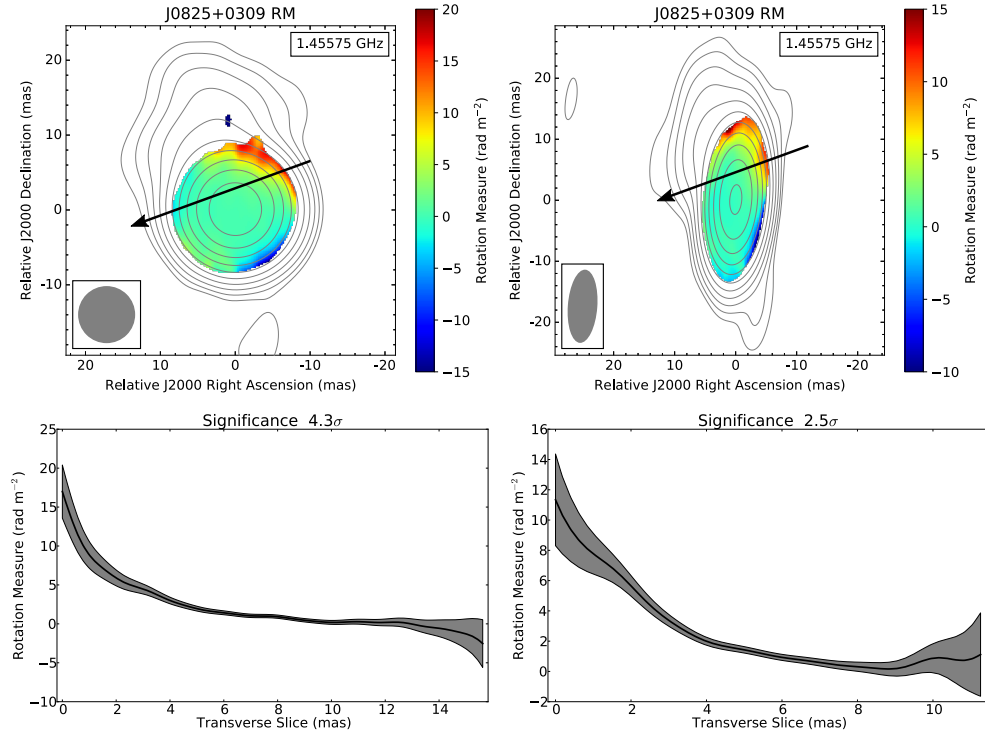


Figure C.8: The corresponding slices for the maps made with the 2.2 GHz beam are shown in Appendix C.2.

C.1.9 J0854+2006

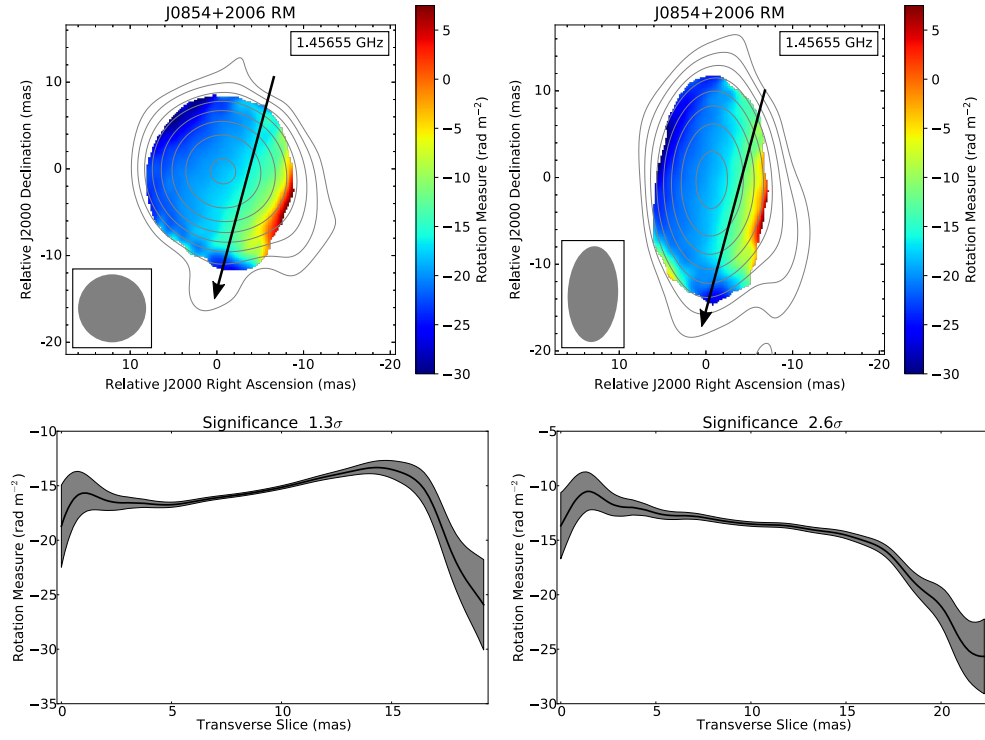
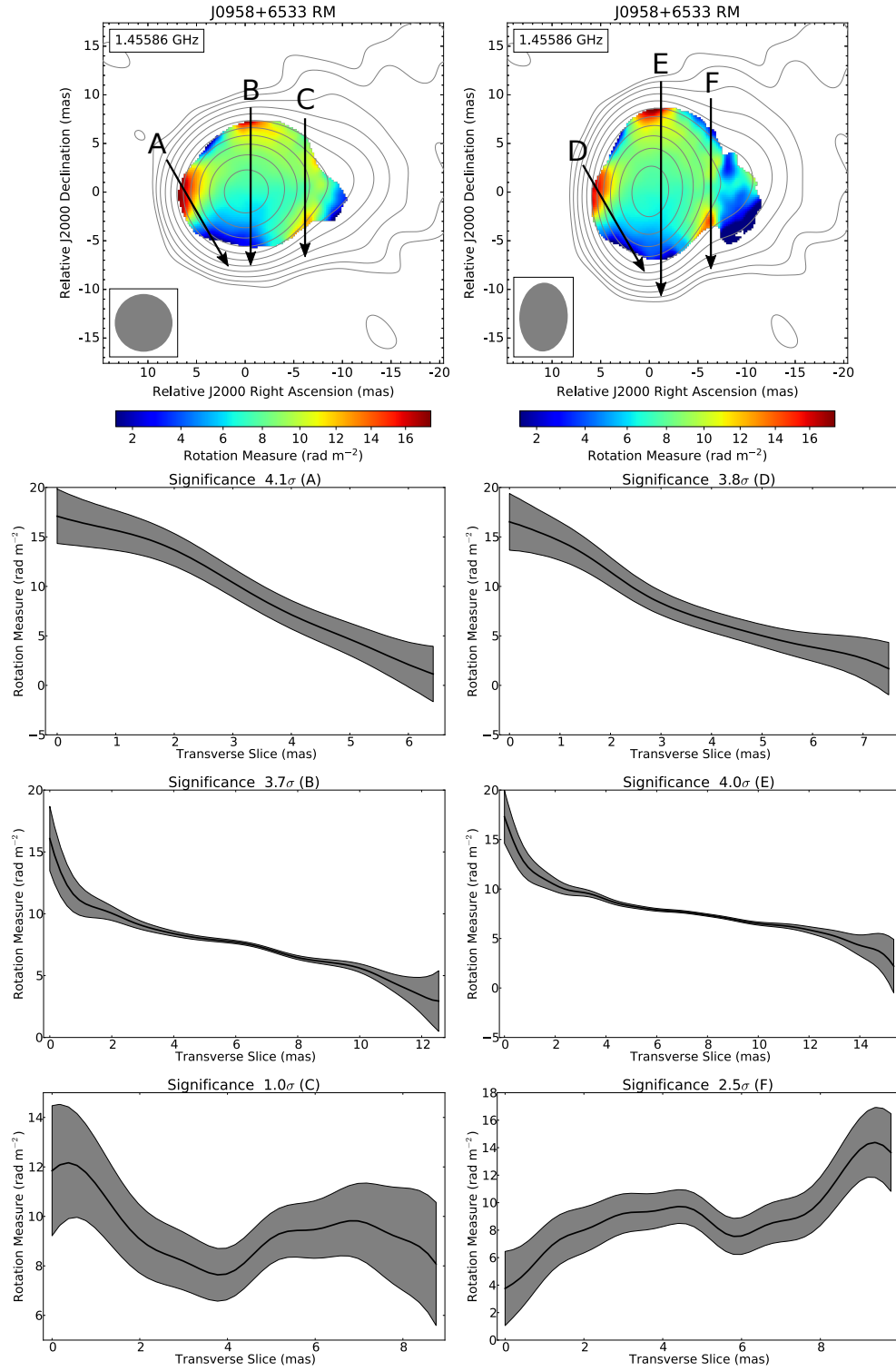


Figure C.9: The corresponding slices for the maps made with the 2.2 GHz beam are shown in Appendix C.2.

C.1.10 J0958+6533

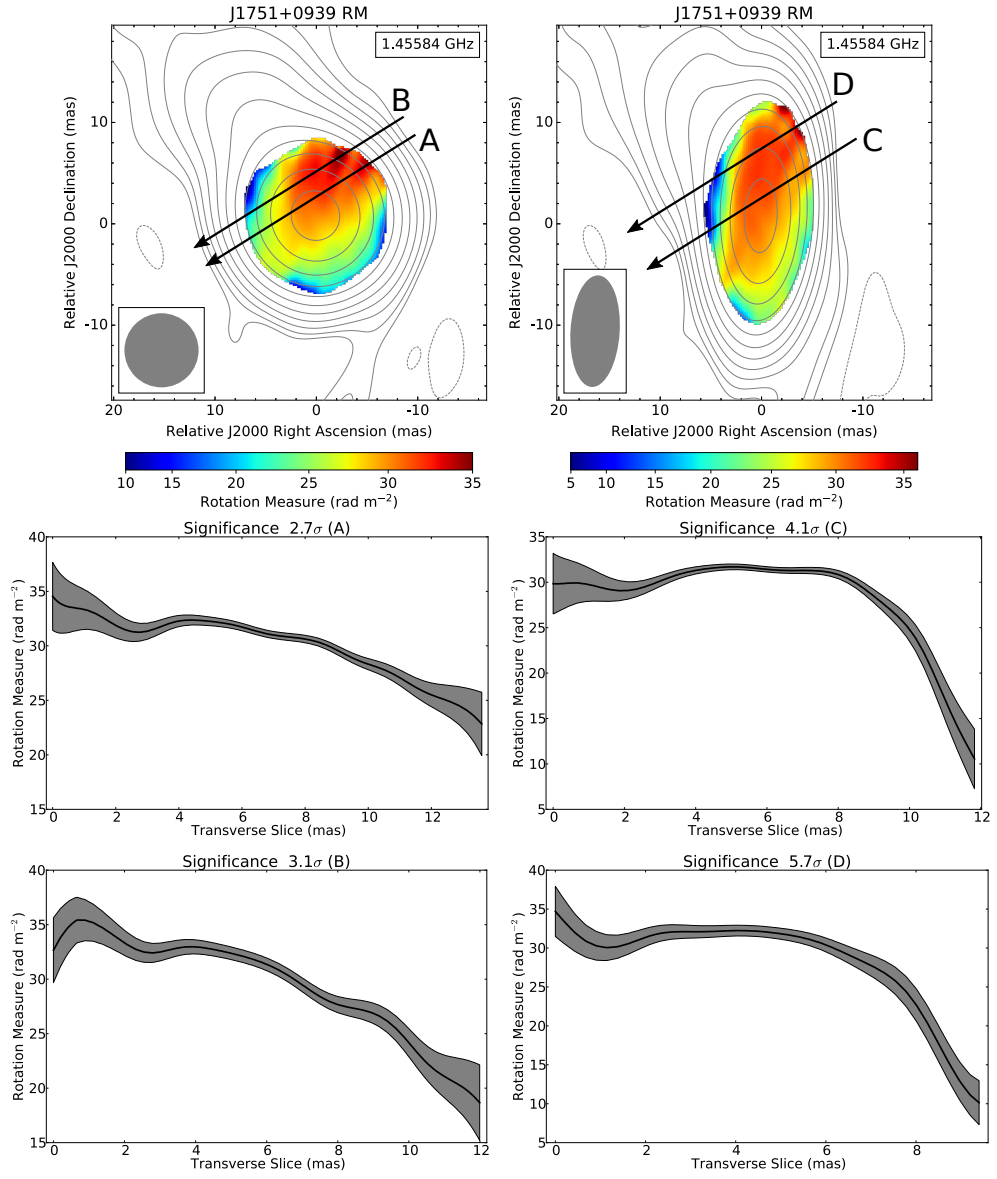
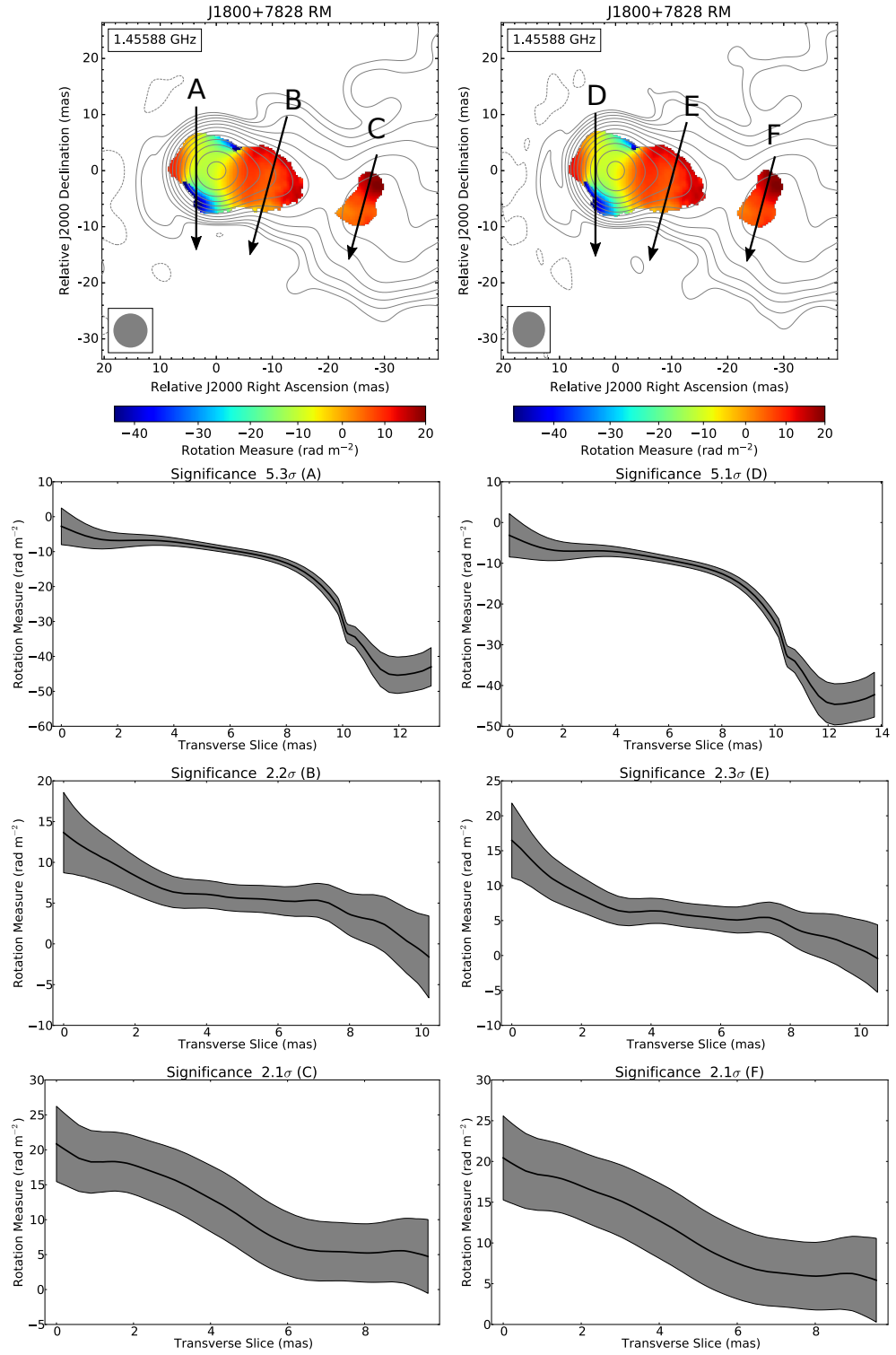
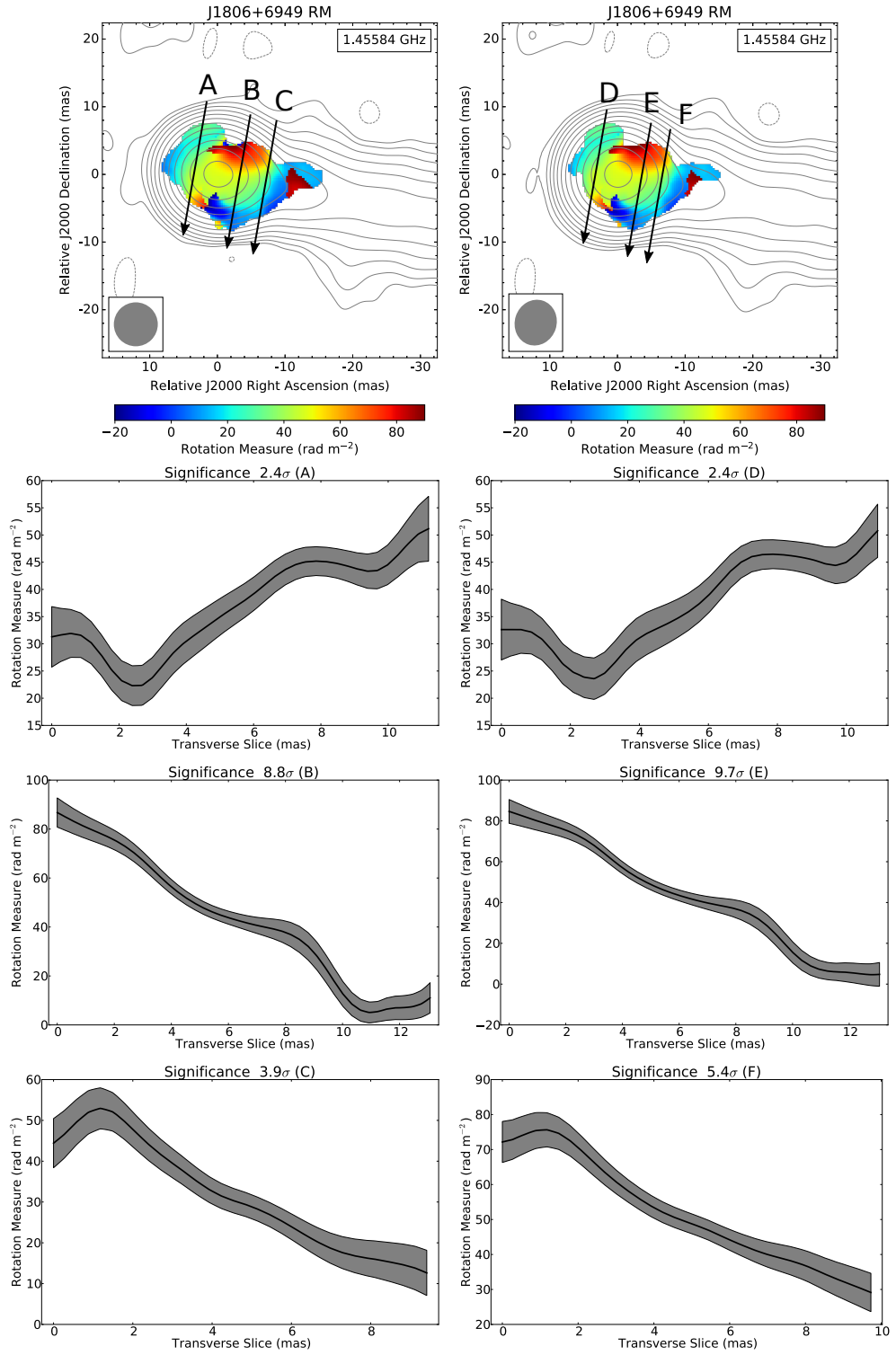
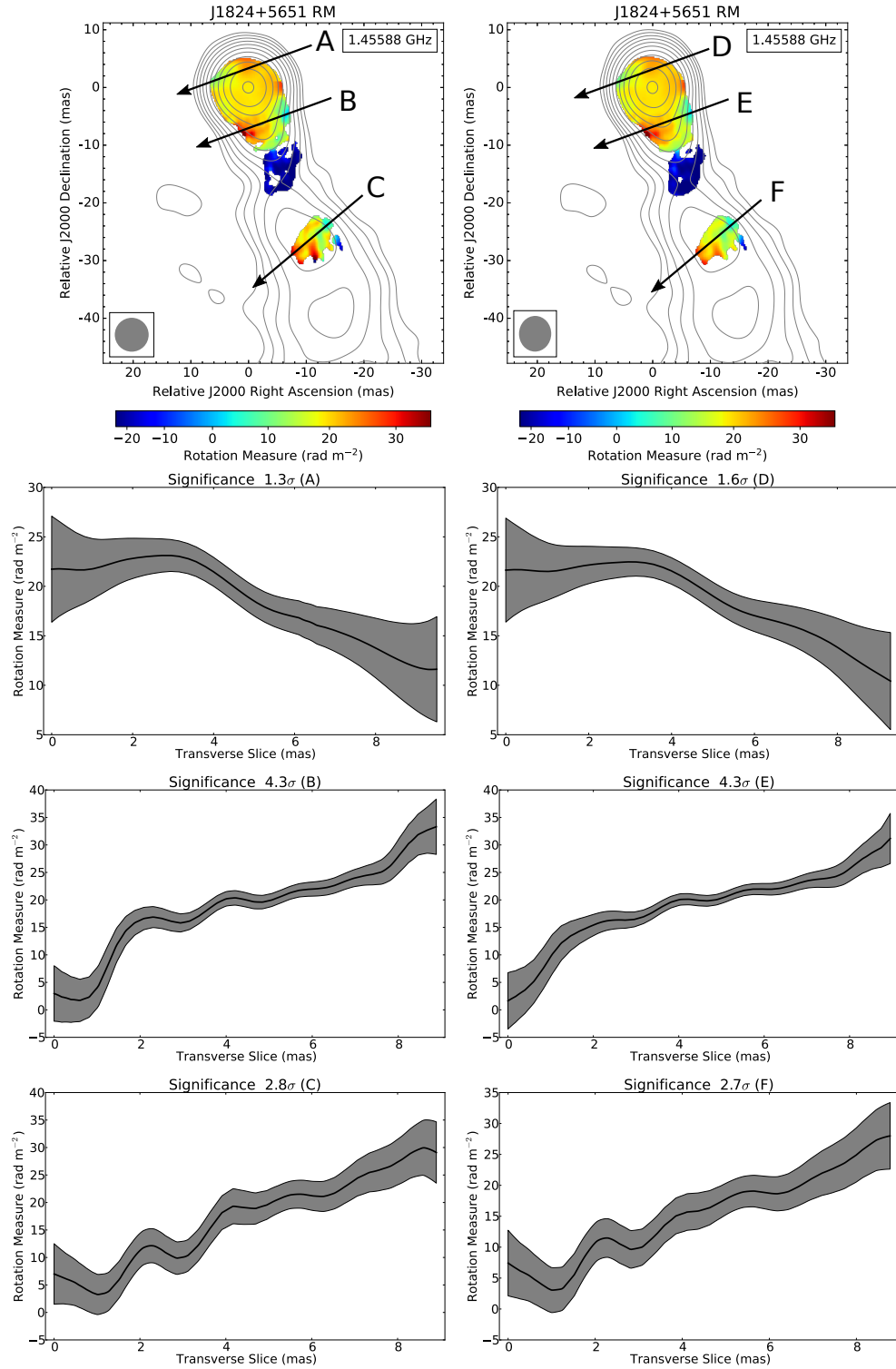
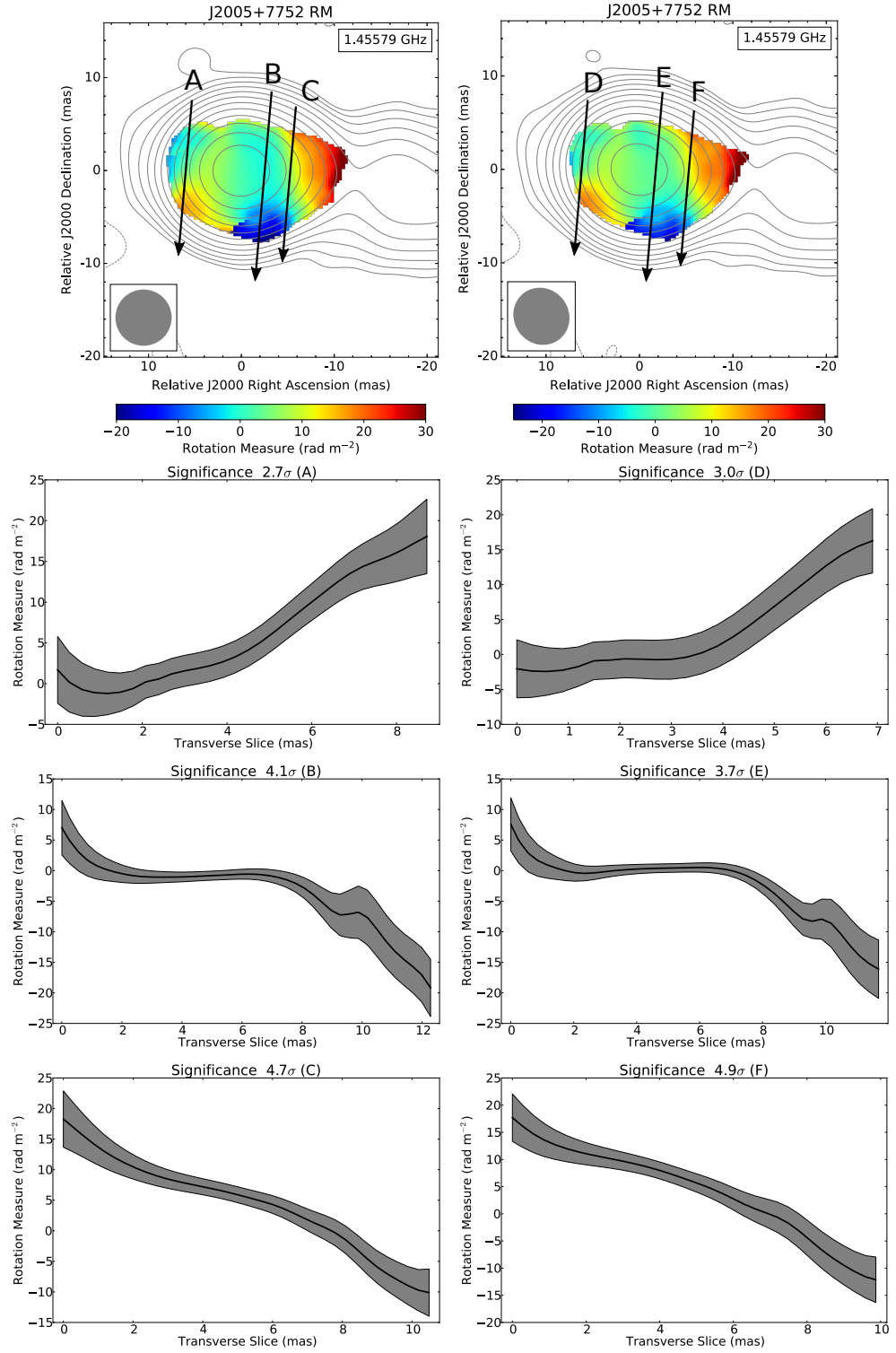
C.1.11 J1751+0939

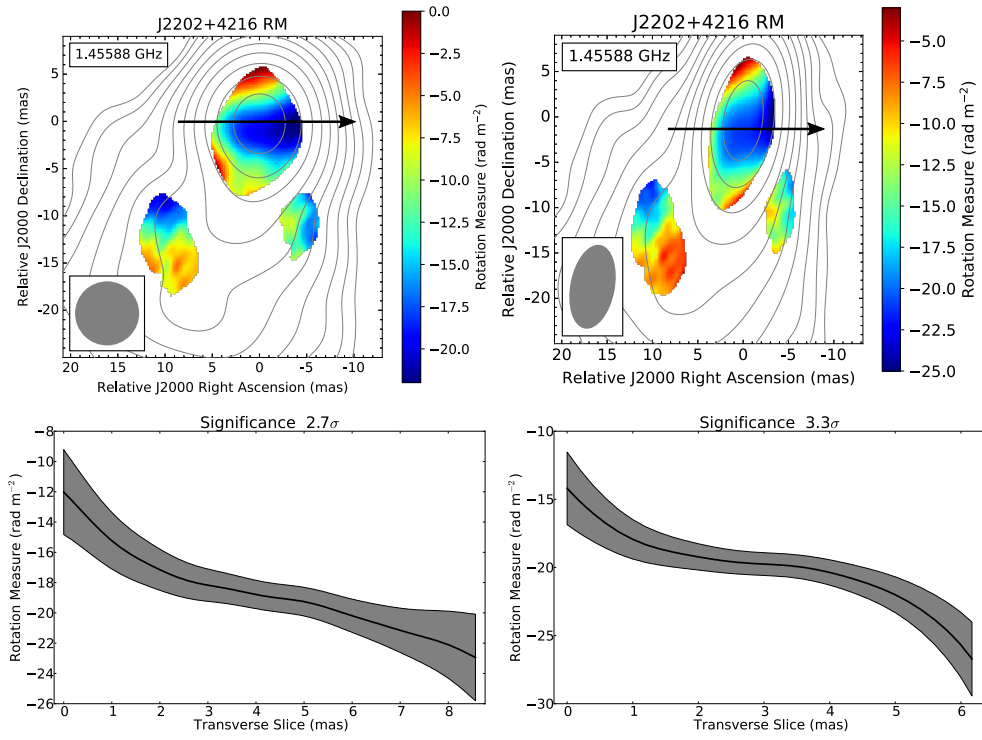
Figure C.11: The corresponding slices for the maps made with the 2.2 GHz beam are shown in Appendix C.2.

C.1.12 J1800+7828

C.1.13 J1806+6949

C.1.14 J1824+5651

C.1.15 J2005+7752

C.1.16 J2202+4216

C.2 S Beam

C.2.1 J0006-0623

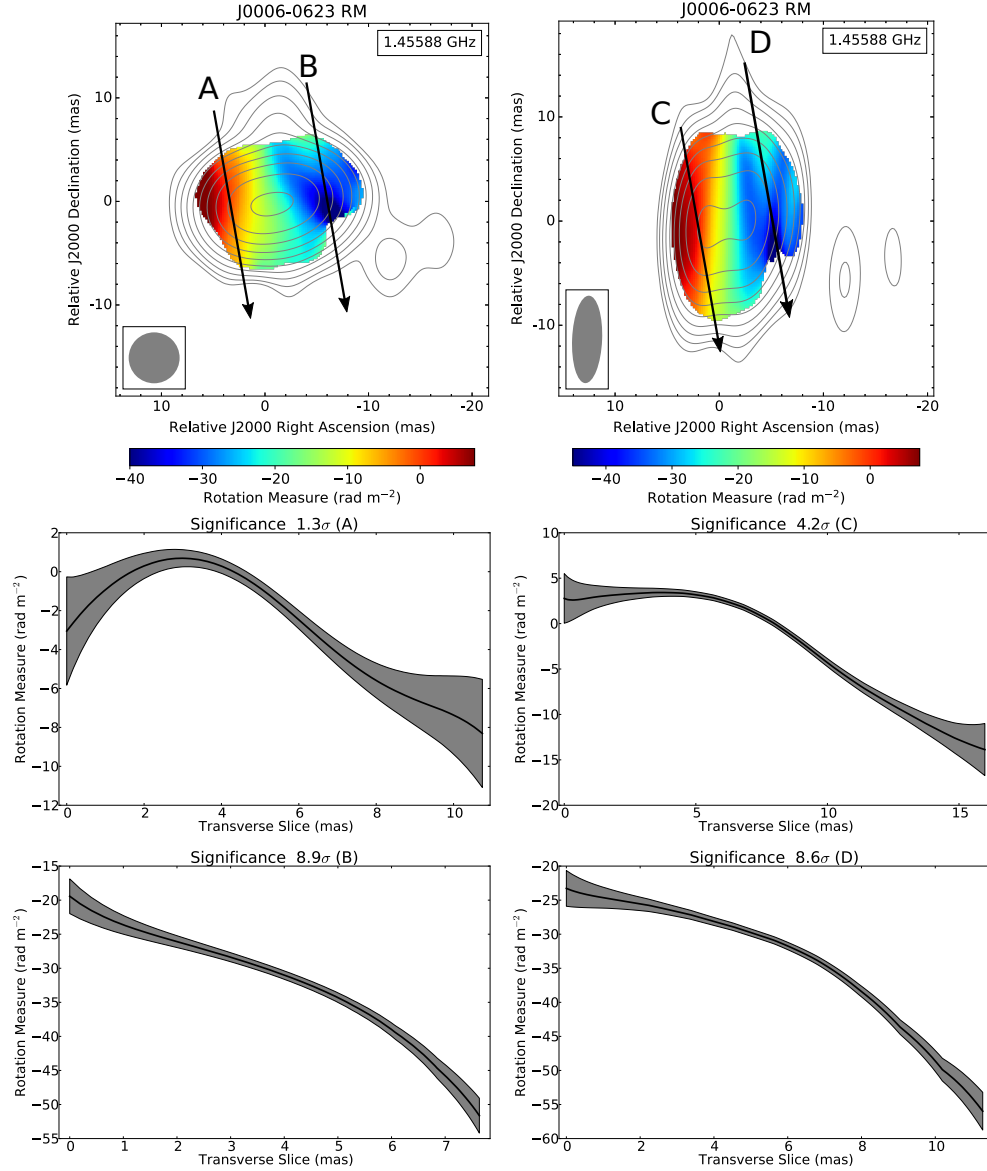
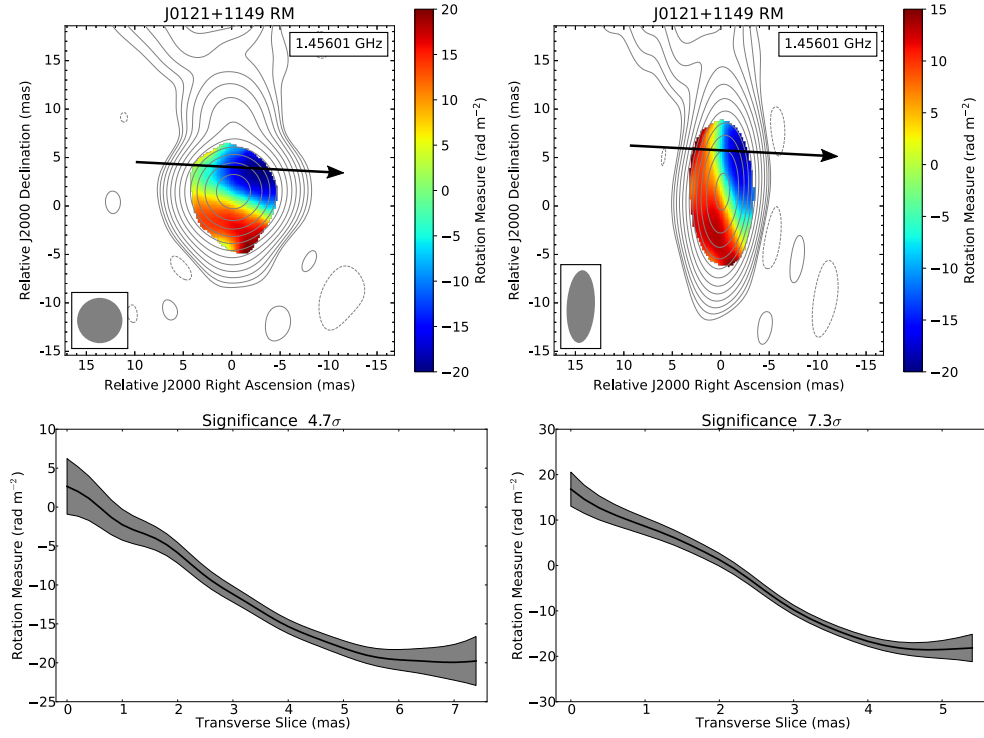
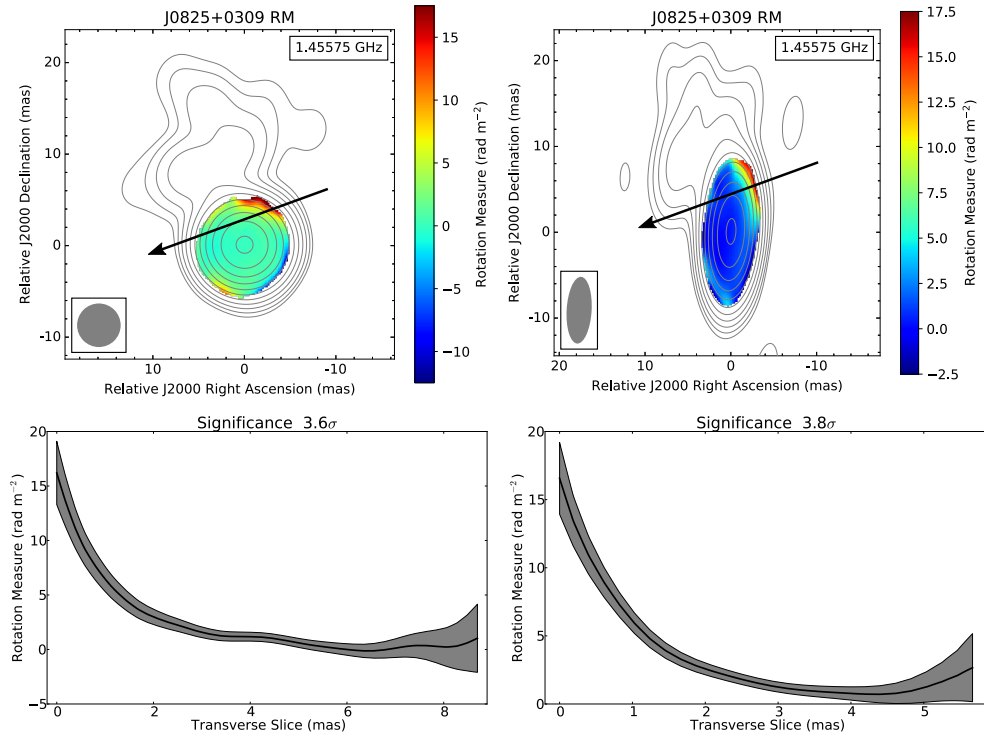


Figure C.17: These 2.2 GHz slices show the reliability of the transverse RM gradient in the jet (slices B and D) as opposed to the possible gradient in the core region (slices A and C). The higher core significance in the elliptical beam slice is due to distortion of the RM distribution along the jet by the very elliptical beam.

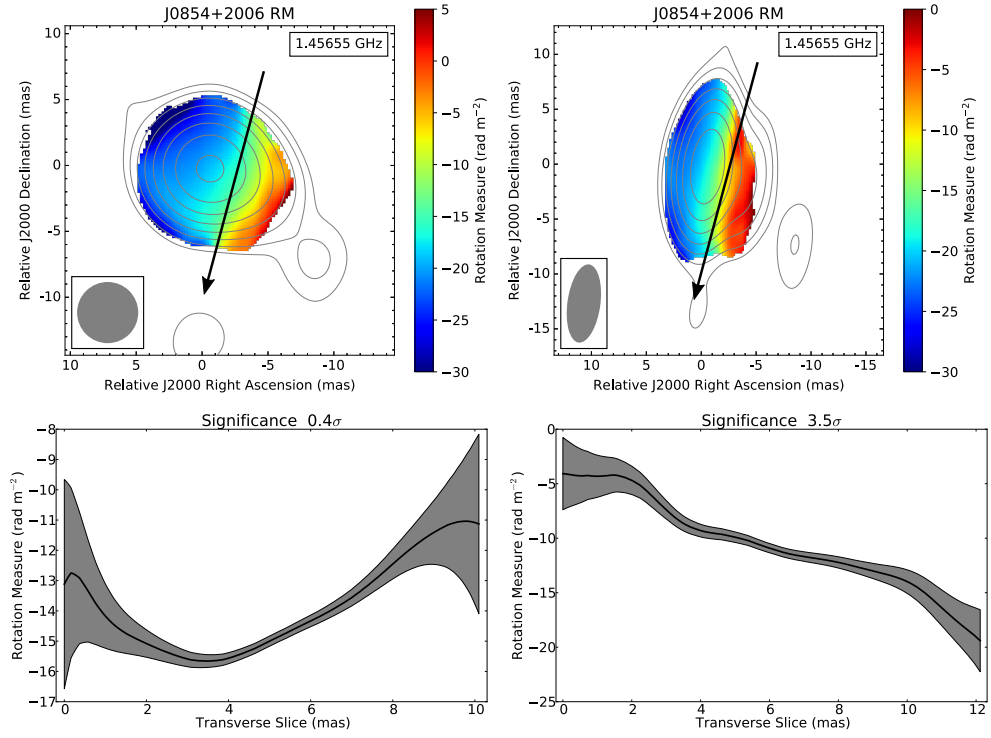
C.2.2 J0121+1149



C.2.3 J0825+0309



C.2.4 J0854+2006



C.2.5 J1751+0939

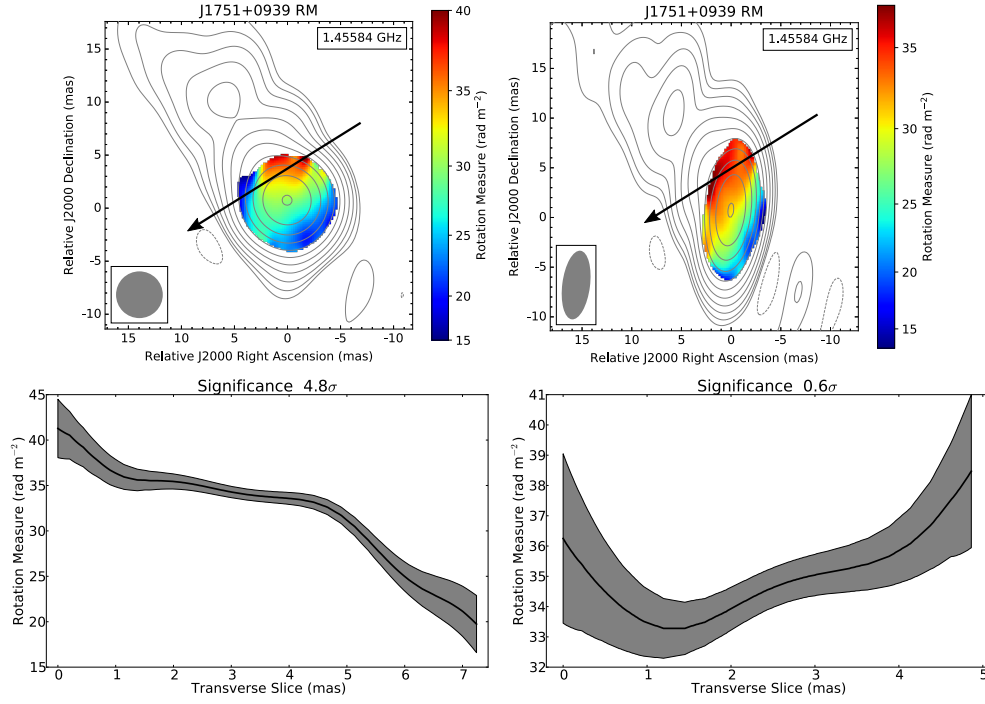


Figure C.21: Although the slice through the circular beam RM map seems promising, the fact that there is no hint of this gradient in the elliptical beam RM map shows that this transverse RM gradient cannot be considered reliable.

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