Extended Circular Polarization in the Jet of 3C84

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Abstract

We report the observation of an extended distribution of circular polarization in the parsec-scale radio jet of 3C84 at 5 GHz with the Very Long Baseline Array (VLBA). These observations demonstrate, for the first time, that circular polarization can be produced in extended regions of the jet, well away from the VLBI core. Although more work is necessary to confirm the detailed morphology, the circular polarization distribution seems to trace some structure underlying or embedded in the overall 5 GHz intensity distribution, possibly a jet or a sheath/lobe surrounding a jet.

Introduction

Circular polarization from extra-galactic radio jets comprises a tiny, but potentially important fraction of their radio emission. Circular polarization may be produced either as an intrinsic component of the emitted synchrotron radiation or as a bi-refringence effect which converts linear to circular polarization (*Faraday conversion*) as the radiation propagates through the jet. Regardless of mechanism, circular polarization can provide unique constraints on the magnetic field and particle population within relativistic jets (e.g. Homan 2005). To realize the promise of circular polarization as a probe of jet physics, we need to study it at high resolution to see where and how the circular polarization is being produced near the base of the jet.

In recent years, the high sensitivity and gain stability of the VLBA has made it possible to reliably detect and image very low levels of circular polarization at parsec-scale resolution (e.g. Homan & Wardle 1999; Homan, Attridge, & Wardle 2001), down to 0.2% to 0.3% of the local Stokes I emission. When it is detected, circular polarization is almost always coincident with or very near the observed VLBI "core," which contains the $\tau = 1$ surface (Homan 2005). This is perhaps not surprising as theory predicts that circular polarization should be strongest when the optical depth is near unity (e.g. Jones 1988). Additionally, circularly polarized signals are a very small fraction of Stokes I, making it possible to detect them only in very strong components which tend to be near the base of the jet.

3C84 is one of a handful of sources that was repeatedly detected in integrated circular polarization measurements made 30 years ago where it showed predominantly a negative sign of circular polarization at frequencies up to 8 GHz (Weiler & de Pater 1983, and sources therein). More recent VLBA measures at 15 and 22 GHz show that 3C84 has a complex distribution of very strong circular polarization (up to 3% of the local I) near the base of its jet and displays both signs of circular polarization (Homan & Wardle 1999, 2004; and see figure 2). Homan & Wardle (2004) used spectral measurements of the circular polarization to show that it was most likely produced by Faraday conversion of linear to circular polarization.

Here we present the first VLBA circular polarization images of 3C84 at 5 GHz. These images show that circular polarization extends well beyond the core region at this frequency and has an intriguing morphology.

Observations And Calibration

We observed 3C84 with the VLBA at 5, 8, and 15 GHz during February 1997 and again at 5, 8, 15, and 22 GHz during December 1997. Here we present the 5 GHz results from these observations. The two observations were part of two different programs and were calibrated differently. In February 1997, 3C84 was a calibrator source and received approximately 25 minutes of integration time in several scans spread in hour angle at each of the frequencies observed. In December 1997, 3C84 was our main target, receiving 2 hours of integration time at each frequency and excellent (u,v)-plane coverage.

For total intensity and linear polarization, standard calibration techniques were used for both experiments. For circular polarization, the February 1997 observations were calibrated using the standard *gain-transfer* technique described by Homan & Wardle (1999), and further details are given in the poster by Gabuzda and Vitrishchak at this conference. The December 1997 observations were calibrated using a completely different technique which reconstructs the circular polarization distribution from residuals of the calibration which assumes zero circular polarization. This reconstruction technique is described in detail by Homan & Wardle (2004).

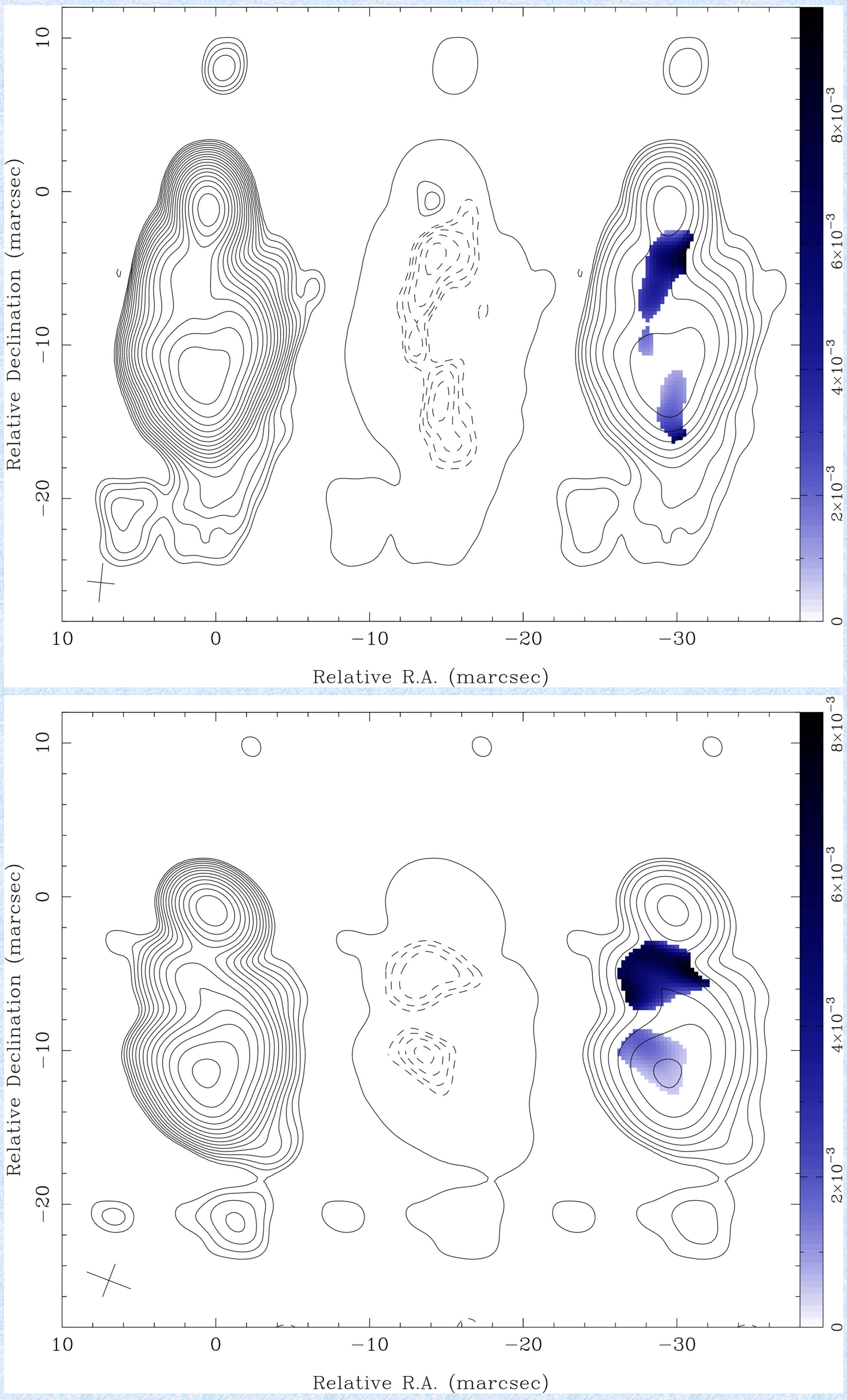

Fig. 1. VLBA images of 3C84 at 6cm. The images on the left are Stokes-I contours (steps × √2). The images in the middle are Stokes-V (circular polarization) contours (steps × √2) with one Stokes-I contour to show registration. The images on the right are fractional circular polarization (color) superposed on Stokes-I contours (steps × 2). **Top frame:** VLBA data from December 1997 with data calibrated using the zero-V reconstruction technique. I contours begin at 5 mJy/beam. V contours begin at ± 1 mJy/beam. **Bottom frame:** VLBA data from February 1997 with data calibrated using the transfer of gains technique. I contours begin at 30 mJy/beam. V contours begin at ±1.5 mJy/beam.

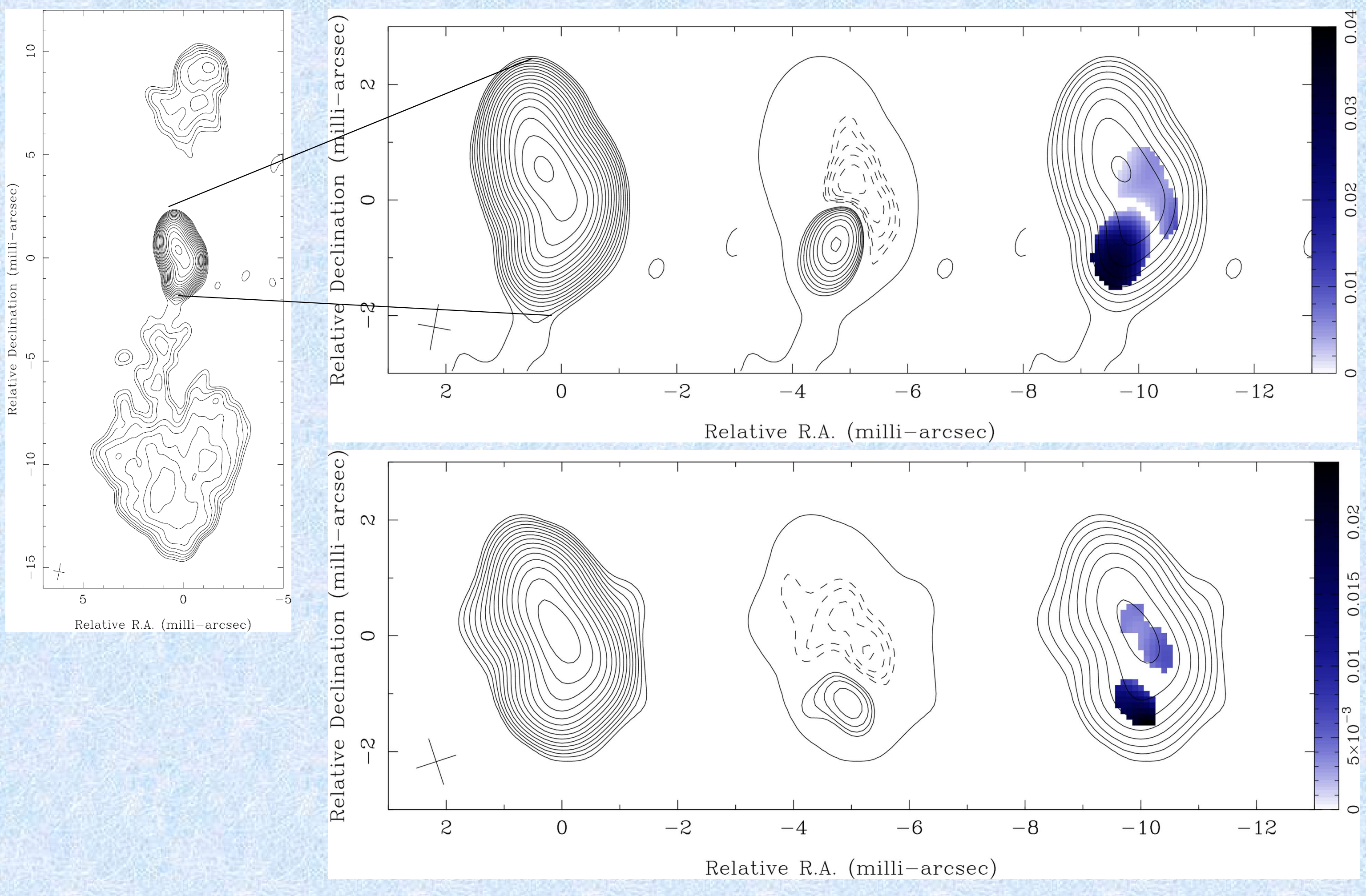

Fig. 2. VLBA image of 3C84 at 2cm. The left-most, single image is a total intensity map of all the parsec-scale structure visible to the VLBA at 2cm. The right, multi-panel image is an enlarged composite of Stokes-I and Stokes-V for the core region with the same layout as described for figure 1. Both positive and negatively circularly polarized regions are visible in both datasets. **Top frame:** Image from Homan & Wardle 2004: VLBA data from December 1997 with data calibrated using the zero-V reconstruction technique. I contours begin at 10 mJy/beam. V contours begin at ± 2 mJy/beam. **Bottom frame:** VLBA data from February 1997 with data calibrated using the transfer of gains technique. I contours begin at 20 mJy/beam. V contours begin at ±5 mJy/beam.

Results and Discussion

Figure 1 displays our 5 GHz circular polarization images of 3C84 from the two sets of observations. The December 1997 observations (top of figure 1) are clearly deeper; however this is to be expected given the longer integration time and improved (u,v)-coverage. Both images show strong, negative circular polarization south of the VLBI core in the optically thin region of the jet. The circular polarization appears both in the jet, just below the core, and again in the southern 'lobe-like' region between 10 and 18 milli-arcseconds south. Both images have approximately the same fractional levels in these two regions with about 0.6% circular polarization in the jet below the core and about 0.2-0.3% local circular polarization in the 'lobe'.

The December 1997 image shows the circular polarization stretched out into a jet-like morphology which seems to trace into the center of the 'lobe'. Given the potential difficulties of the circular polarization reconstruction technique used for this image (Homan & Wardle 2004), we are not yet completely confident of the details of this morphology; however we note that the circular polarization detected by our other observations with a completely different calibration approach lie along this same path. This path also approximately matches that of the jet seen at higher frequencies (see figure 2) which connects the core with the 'lobe', so we may be seeing a central channel through this region which is circularly polarized.

We detect no linear polarization from 3C84 which is probably depolarized externally[1]; however, the circular polarization tells us that there must be ordered field in this region. The consistent sign of circular polarization through this region suggests that the same field order characteristics (most likely field polarity or helical pitch angle, e.g. Homan et al. 2001) persist along this length of the jet.

Figure 2 displays our 15 GHz VLBA circular polarization results. Again, both observations, although they are calibrated quite differently show essentially the same result of strong circular polarization (up to 3% of the local Stokes I!) which changes sign from negative to positive circular polarization at the base of the core region. The top image in figure 2 was originally published by Homan & Wardle (2004) along with a very similar 22 GHz image.

In Homan & Wardle 2004, we suggested the change in sign from negative to positive circular polarization was due to a decrease in observed opacity at the end of the core region. This may well be the case, but clearly the sign changes back to negative circular polarization further out in the jet as seen in our 5 GHz images. The second change in sign cannot also be due to opacity effects, so some change in the field order producing the circular polarization must be present between the core region and the jet beyond about 2 milli-arcseconds from the core.

The levels of circular polarization seen at 5 GHz are smaller than those at 15 GHz and decrease with increasing distance from the core region. The entire region where the CP is produced at 5 GHz is optically thin (Walker et al. 2000), so decreased opacity is unlikely to be the main cause of the decreased levels of circular polarization along the jet. Most likely it is due some combination of (1) decreased degree of ordered magnetic field along the jet and/or (2) increasing dilution from emission which has no significant circularly polarized component

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[1] An external depolarizing screen will have a much smaller (if any) effect on circular polarization as compared to linear polarization.