Probing the extended emission-line region in 3C 171 with high-frequency radio polarimetry

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ABSTRACT
I present high-frequency polarimetric radio observations of the radio galaxy 3C 171, in which depolarization is associated with an extended emission-line region. The radio hotspots, known to be depolarized at low radio frequencies, become significantly polarized above (observer’s-frame) frequencies of 15 GHz. There is some evidence that some of the Faraday rotation structure associated with the emission-line regions is being resolved at the highest resolutions (0.1 arcsec, or 400 pc); however, the majority remains unresolved. Using the new radio data and a simple model for the nature of the depolarizing screen, it is possible to place some constraints on the nature of the medium responsible for the depolarization. I argue that it is most likely that the depolarization is due not to the emission-line material itself but to a second, less dense, hot phase of the shocked ISM, and derive some limits on its density and temperature.

Key words: galaxies: active – galaxies: individual: 3C 171 – galaxies: ISM

1 INTRODUCTION
Extended emission-line regions (EELR) around radio galaxies are common, and often aligned with the axes of the extended radio emission (e.g. McCarthy et al. 1987; McCarthy 1993; McCarthy, Baum & Spinrad 1996). There is considerable debate as to whether EELR are ionized by photons from the nucleus or by shocks driven by the jets (e.g. Tadhunter et al. 1998). Most EELR around low-redshift sources can adequately be described by central-illumination models, while sources which show evidence for shock ionization (such as extreme emission-line kinematics) are largely at high redshift. However, there is evidence that a small minority of low-redshift radio galaxies are also more adequately described by a shock-ionization model. If the ionization is due to shocks, the physical conditions in and kinematics of the EELR may give us important information about the energetics of the radio source as a whole.

One good candidate low-redshift shock-ionization source is 3C 171, an unusual \( z = 0.2384 \) radio galaxy. Its large-scale radio structure has been well studied (Heckman, van Breugel & Miley 1984; Blundell 1996). In its inner regions it is similar to a normal FRII, but low-surface-brightness plumes instead of normal lobes extend north and south from the hotspots. High-resolution images show knotty jets connecting the radio core with the hotspots (Hardcastle et al. 1997). 3C 171 is associated with a prominent EELR, elongated along the jet axis. Heckman et al. found that the emission-line gas was brightest near the hotspots, suggesting that the radio-emitting plasma is responsible for powering the emission-line regions. More recently Clark et al. (1998) have made WHT observations of the emission-line regions and shown that their ionization states are most consistent with a shock-ionization model. The unusually strong EELR in this source may be indicative of an environment unusually rich in dense, warm gas; the interactions between the jets and this gas might then be responsible for the peculiar large-scale radio structure.

Heckman et al. pointed out the depolarization of the radio source near the hotspots at frequencies up to 15 GHz. The strong spatial relationship between the EELR (or the material traced by the EELR) and depolarization was pointed out by Hardcastle et al. (1997), who superposed an 8-GHz Very Large Array (VLA) image on the \textit{Hubble Space Telescope (HST)} snapshot (de Koff et al. 1996) in the F702W filter (which at this redshift passes several strong lines). The source has since been observed with a number of other \textit{HST} filters, and Fig. 1 shows a superposition of the 8-GHz map on an \textit{HST} image in the [OIII]495.9/500.7 nm lines. Regions of low polarization in the radio map can be seen to correspond to the positions of emission-line material. The eastern hot spot is almost completely unpolarized at 8 GHz and below, while the western hot spot is partially depolarized.

The close association between the emission-line regions and the radio depolarization in 3C 171 opens up the possibility of using radio data to constrain unknown physical conditions, such as the electron number density and the magnetic field strength in the gas surrounding the source. In this paper, I present new radio observations of 3C 171, and discuss the constraints that they place on the nature of its environment.

Throughout the paper, I use a cosmology with \( H_0 = 65 \) km
2 OBSERVATIONS AND ANALYSIS

The degree of depolarization is in general expected to be reduced at higher frequencies and higher resolutions. As parts of 3C 171’s hotspots had been found to be completely depolarized at the full resolution of the VLA (≈ 0.25 arcsec) at 8.1 GHz, I elected to observe the source with the A and B arrays of the VLA at the U and K bands, ≈ 15 and ≈ 22 GHz. In addition, I made use of the A-array 8.1-GHz observations discussed by Hardcastle et al. (1997).

Details of the observations used are listed in Table 1. The new observations were carried out in fast-switching mode with an integration time of 3.3 s, using frequent observations of a nearby bright point-source calibrator, 0749+540. The cycle time used was 320 s, with 80 s on calibrator and 240 s on source, giving typical times of 50 s on the calibrator and 210 s on source after dead time due to slewing. (The low efficiency was due to the lack of a good nearby calibrator.) Primary referenced pointing was carried out, using short X-band observations of 0749+540 taken every hour, to avoid loss of sensitivity due to VLA pointing errors. The observations were made with two nearby observing frequencies (Table 1) with a 50-MHz bandwidth in each. 3C 286 was used as the flux and polarization position angle calibrator. The data were reduced in a standard manner within AIPS. ELINT was used to correct for the dependence of antenna gain on elevation. The use of fast-switching mode led to observations which were very well phase- and amplitude-calibrated after the standard calibration procedure: however, there was enough signal for a single iteration of phase self-calibration for each dataset, which gave a marginal improvement in image quality. Finally, the A- and B-array datasets were combined using DBCON, UVFIX was used to align the datasets at the three wavelengths at the radio core, using the K-band dataset as the reference, and final images were made using IMAGR, combining the data from the two observing frequencies in each band. This resulted in images at effective frequencies of 8.09, 14.94 and 22.46 GHz. For simplicity, these frequencies will be referred to as 8, 15 and 22 GHz from now on.

3 RESULTS

Initially, images at the full resolution of the data were made: the image properties are listed in Table 1. These images were made using a matched shortest baseline of 18 kλ, and so are in principle sensitive to structures on the same angular scales: in practice, however, large-scale structure is resolved out at higher frequencies, and the steep spectrum of the source at high frequencies (Blundell

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1 See http://info.aoc.nrao.edu/vla/html/highfreq/hffastswitch.html

1996) also reduces the probability of detecting the lobes at 15 and 22 GHz.

In total intensity, the differences between the images are therefore predictable. The radio core is detected at all three frequencies, with flux densities of 1.8, 3.4 and 2.5 mJy at 8, 15 and 22 GHz respectively, giving it a steep spectrum at the higher frequencies. The compactness of the hotspots, which are only just resolved at the full resolution at 22 GHz, and are therefore only tens of milliarcsec (hundreds of pc) in size (Fig. 2). The W hotspot shows a well-resolved extension to the N, which may be tracing the current direction of outflow from the hotspot, while the E hotspot shows a striking bow-shock-shaped extension around the central compact component, superposed on a N-S filament. The hotspots have steep spectra at these high frequencies: the integrated spectral indices in the hotspots are $\alpha_{8}^{15} = 0.92$ and $\alpha_{15}^{22} = 1.38$ (W hotspot) and $\alpha_{8}^{15} = 1.08$ and $\alpha_{15}^{22} = 1.58$ (E hotspot).

In polarization, however, the data clearly show the E hotspot to be polarized at 15 and 22 GHz, although it is essentially unpolarized at 8 GHz and below. The partial depolarization of the W hotspot also disappears at high frequencies. Some of this might be thought to be due to simple beam depolarization in the low-resolution 8-GHz images; there clearly is some polarization structure in the E hotspot in the images of Fig. 2. To investigate this, I made images at lower resolutions, matched to the resolution of the 8-GHz data, using appropriate weighting and tapering of the $u$, $v$ plane, and compared the integrated total and polarized fluxes of the two hotspots at different resolutions using the AIPS verb IMSTAT, measuring using boxes which are shown in Fig. 2. Beam depolarization effects should be independent of frequency, to a first approximation, although the effects of spectral index mean that we are not seeing exactly the same structures at each frequency: considering the hotspot regions only should minimize these effects. Depolarization due to a Faraday-rotating medium should have a strong frequency dependence. The results of the measurements are given in Table 2.

It can be seen from these measurements that the dominant effect is frequency-dependent. The fractional polarization of the two hotspots increases with increasing frequency even in images made with matched resolutions. The total polarized flux remains approximately constant with frequency in the W hotspot and increases with frequency in the E hotspot. Since the flux measured in total intensity falls steeply with frequency, we can be certain that this is not simply a spectral index effect: a contaminating, highly-polarized component would have to have a flat or inverted spectral index. There is some evidence for beam depolarization effects in the differences between the fractional polarizations observed at different resolutions with the same frequency, particularly at 22 GHz, but this is clearly not the most significant effect.

There is some limited evidence for Faraday rotation associated with the region of depolarization. This is illustrated in Fig. 2, which shows the depolarization and rotation between 15 and 22 GHz at a resolution matched to the 8-GHz map. The most significant rotation is in the N part of the E hotspot. However, there is no particularly strong relationship between Faraday rotation and depolarization, and the rotation is never particularly large (modulo possible 180° rotation effects).

4 INTERPRETATION

We can begin by making the assumption that the depolarizing medium is external to the source. This is justified by the extremely good, though not perfect, association between the EELR and the depolarization. No model places the EELR inside the radio source – it is spatially quite distinct from, and physically larger than, the radio emission at various points (Fig. 1) – and at the same time it is clearly related to the depolarization. We can therefore treat the depolarizing material as an external screen of dimensions comparable to those of the EELR.
The situation is then a classical problem in the theory of radio polarization, discussed by Burn (1966). If a screen is external, two extreme cases can be identified. In the first, the Faraday screen is fully resolved by the telescope beam: in this case, no depolarization should be observed, but Faraday rotation should be seen. Some sources in rich cluster environments appear to be in this regime, in that the Faraday screen is partially or fully resolved (e.g. Perley & Carilli 1996). In 3C 171, however, we see significant depolarization without much associated Faraday rotation, as Fig. 3 shows. This is likely to be due to a largely unresolved foreground screen. In the limit that the size scale $d$ of the individual depolarizing regions (regions of uniform magnetic field) is much smaller than the resolution element, and is well defined, and that there are many regions along each line of sight, the degree of polarization $p$ of a part of the source seen through such a screen at a given frequency $\nu$ is given by

$$p = p_i \exp \left[ -2K^2 (n_e B_\parallel)^2 dRc^5 \nu^{-4} \right]$$

(Burn 1966) where $p_i$ is the intrinsic polarization, $K$ is a constant with value $8.12 \times 10^{-3}$ rad nT$^{-1}$ m kpc$^{-1}$, $(n_e B_\parallel)^2$ is the dispersion in the product of number density and magnetic field strength and $R$ is the line-of-sight depth through the medium.

We can try to apply this model to the observations, but there are a number of reasons why it should be treated with caution. The
first is a practical one: the measurements of the polarized intensity of the hotspots clearly include regions with different degrees of polarization (Fig. 3) and so, presumably, different physical conditions in the depolarizing screen. At best we will obtain some emission-weighted average of the physical conditions. To reduce this effect, I consider below only the E hotspot, which exhibits more uniform depolarization. The model is also not realistic. It assumes a single physical size scale for the variations in Faraday depth, parametrized by \( d \). As Laing (1984) points out, realistic screens will have a range of scale sizes, which tends to wash out the sharp cutoff in polarization at low frequencies. This is probably the case for our observations: the degree of polarization at 8 GHz, though low, is still too high to be fitted with a simple model of the form of eq. (4). If we write eq. (4) as \( p = p_i \exp(-C \nu^{-\alpha}) \), then we can solve for \( C \) and \( p_i \) using the 15 and 22 GHz data at 0.3 \( \times \) 0.2-arcsec resolution, obtaining (for the E hotspot) \( C \sim 1.3 \times 10^{41} \) Hz\(^2\), \( p_i = 7.1 \) per cent: we would then expect the degree of polarization at 8 GHz to be essentially zero (about \( 10^{-5} \) per cent) whereas in fact there is a detection of polarization in this region at the 5\( \sigma \) level (Table 5). The intrinsic polarization \( p_i \) obtained here is also somewhat low, which suggests that the model is not accurate even for the two higher frequencies. However, the value of \( C \), which is the critical quantity for estimating physical parameters, simply depends logarithmically on the ratio of the polarizations at the two frequencies, and so is unlikely to be grossly wrong. Applying the model, we can see from the HST data, assuming a cylindrical symmetry, that \( R \sim 5 \) kpc: this would imply \( (n_e B r) \parallel d \approx 2 \times 10^5 \) m\(^{-3}\) nT kpc\(^{-1}\). If we further assume a simple model in which the differences are due to varying orientations of the magnetic field in an approximately uniform-density (though possibly low-filling-factor) medium, then, dropping numerical factors of order unity, \( n_e B d \approx 10^5 \) m\(^{-3}\) nT kpc\(^{-1}\). (If there are in fact variations in \( n_e \), then the \( n_e \) value derived from this equation is a weighted average.)

Unfortunately, none of these three parameters, \( n_e \), \( B \) and \( d \), is well constrained by existing observations. \( B \) values of the order of 1 nT are energetically plausible from equipartition arguments, but this estimate is good to an order of magnitude at best. We know that \( d < 1 \) kpc for the model above to be either necessary or applicable; the fact that the degree of polarization of the hotspots continues to increase at higher radio resolutions (Table 5) suggests, however, that at least some structure is present on scales \( \sim 100 \) pc.

The density is the most problematic quantity. Clark et al. (1998) suggested that the density in the emission-line clouds in the nuclear regions is \( \sim 300 \) cm\(^{-3}\), but were unable to make measurements near the hotspots. Electron densities \( \sim 100 \) cm\(^{-3}\) are often quoted for EELR. However, it is important to emphasise that it is probably not the line-emitting material itself that is depolarizing the radio source, if it has a density close to this value. Baum & Heckman (1989) estimate constraints on the density and mass of the extended line-emitting material in 3C 171, based on the observed H\( \alpha \) luminosity and assuming case B recombination: for a filling factor of unity, they estimate \( n_e = 0.2 \) cm\(^{-3}\). To obtain a density \( \sim 100 \) cm\(^{-3}\), a filling factor of \( \sim 10^{-6} \) would be required: in other words, if the line-emitting material has this density, it will have a very low covering fraction, and cannot be responsible for depolarizing the radio source. For filling factors close to unity, a single-phase medium with a density close to the value given by Baum & Heckman can still just about explain the observations, requiring \( d \sim 1 \) kpc for \( B = 1 \) nT. However, if the EELR consists of dense (\( \sim 100 \) cm\(^{-3}\)), warm line-emitting clouds with a low filling factor, they cannot be responsible for the observed depolarization. It must instead be due to a second phase of the ISM. A plausible candidate is a second, hotter, more diffuse ionized phase, which would be expected to be present in shock-ionization models for the EELR: if the two phases are in approximate pressure equilibrium, then the density of the hot phase can be much lower than in the EELR clouds. If we take \( d \approx 100 \) pc and \( B \approx 1 \) nT, then the depolarization implies \( n_e \approx 1 \) cm\(^{-3}\), which is a plausible density for...
the hot phase in the above scenario. For pressure balance with the
colder, denser EELR clouds, that density would imply $T_{\text{hot}} \sim 10^6$
K; of course, we have no particular a priori reason to expect exact
pressure balance in this dynamic situation.

The non-detection of 3C 171 in a deep ROSAT X-ray observation
(Hardcastle & Worrall 1999) sets quite strict limits on the
properties of any hot gas in the system. I derive a 3$\sigma$ upper limit
on the absorbed ROSAT-band (0.1–2.4 keV) flux of the region of
interest of $\sim 3 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$. If we again assume cylin-
drical symmetry, with $R = 5$ kpc and $l \approx 50$ kpc, and consider
a uniform medium, then Fig. 4 shows the constraints on gas den-
sity and temperature imposed by the X-ray limit together with the
detection of depolarization. It can be seen that plasma of the tem-
perature typically detected in the atmospheres of elliptical galaxies
($T \gtrsim 10^5$ K) cannot be responsible for the depolarization: to avoid
detection in the X-ray, its density would have to be low ($10^{-2} -
10^{-3}$ cm$^{-3}$), implying scales $d > 1$ kpc, which would be resolved
by the radio data. This conclusion is valid so long as $B$ is not very
much larger than 1 nT. The allowed region of parameter space in
Fig. 4 is more or less consistent, given the large uncertainties in all
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temperatures), with the order of magnitude estimate of the t emper-
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Fig. 4. Constraints on the properties of the depolarizing medium. The solid line shows the upper limit on the electron density of the medium as a function of temperature given the ROSAT upper limit discussed in the text. Only regions of parameter space below and to the left of the solid line are permitted by the X-ray upper limit; higher densities or temperatures would produce more X-ray emission than observed. The calculation was carried out using the MEKAL model within XSPEC, assuming 0.5 solar abundances. The dashed line shows the constraint imposed by the fact that the depolarizing medium is not resolved ($d < 1$ kpc), assuming $B = 1$ nT. Only regions of parameter space above this line are permitted by the data, given equation (1). The exact position of the dashed line depends on the magnitude of $B$, and so is uncertain, as discussed in the text. The dotted line shows, for reference, the line of pressure balance with a gas of $T = 10^4$ K, $n_e = 100$
cm$^{-3}$ (plausible parameters for the EELR clouds).

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