Broadband radio circular polarization spectrum of the relativistic jet in PKS B2126–158

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ABSTRACT

We present full-Stokes radio polarization observations of the quasar PKS B2126–158 ($z = 3.268$) from 1 to 10 GHz using the Australia Telescope Compact Array. The source has large fractional circular polarization, $m_c \equiv |V|/I$, detected at high significance across the entire band (from 15 to 90\,σ per 128 MHz sub-band). This allows us to construct the most robust circular polarization (CP) spectrum of an AGN jet to date. We find $m_c \propto \nu^{+0.60\pm0.03}$ from 1.5 to 6.5 GHz, with a peak of $m_c \sim 1\%$ before the spectrum turns over somewhere between 6.5 and 8 GHz, above which $m_c \propto \nu^{-3.0\pm0.4}$. The fractional linear polarization ($p$) varies from $\lesssim 0.2\%$ to $\sim 1\%$ across our frequency range and is strongly anti-correlated with the fractional CP, with a best-fit power law giving $m_c \propto p^{-0.24\pm0.03}$. This is the first clear relation between the observed linear and circular polarizations of an AGN jet, revealing the action of Faraday conversion of linear polarization (LP) to CP within the jet. More detailed modelling in conjunction with high-spatial resolution observations are required to determine the true driving force behind the conversion (i.e. magnetic twist or internal Faraday rotation). In particular determining whether the observed Faraday rotation is internal or entirely external to the jet is key to this goal. The simplest interpretation of our observations favours some internal Faraday rotation, implying that Faraday rotation-driven conversion of LP to CP is the dominant CP generation mechanism. In this case, a small amount of vector-ordered magnetic field along the jet axis is required, along with internal Faraday rotation from the low energy end of the relativistic electron energy spectrum in an electron-proton dominated jet.

Key words: radio continuum: galaxies – galaxies: magnetic fields

1 INTRODUCTION

Large-scale, ordered magnetic fields are invoked to explain the launching, acceleration and collimation of relativistic jets from the central nuclear region of active galactic nuclei (AGN) (Meier 2009). These jets of relativistic plasma can be formed by strong magnetic fields centrifugally lifting particles out of the accretion disk (Blandford & Payne 1982) and/or accelerating a pair plasma cascade near the black-hole horizon (Blandford & Znajek 1977). However, the three-dimensional jet magnetic field structure and particle composition are still not well constrained observationally. Circular polarization (CP), measured as Stokes $V$, in the radio continuum emission from AGN jets is a powerful diagnostic of the jet magnetic field and particles since, unlike linear polarization, it is expected to remain almost completely unmodified by external screens (although see Macquart & Melrose 2000, for the special case of scintillation induced CP).

The integrated emission of radio-loud AGN typically show linear polarizations of a few percent of the total intensity (Stokes $I$), while detections of the degree of CP generally find values ranging from 0.1–0.5\% (Saikia & Salter 1988), with values as large as 1\% being uncommon (Aller & Aller 2012). From a compilation of reliable measurements by Weiler & de Pater (1983) and the monitoring observations of Komesaroff et al. (1984), we know that CP fractions are higher in flat spectrum sources, the CP is more variable than both total intensity and linear polarization (LP) fraction,
there is no clear correlation between LP and CP, and there is a preferred handedness in individual sources. Rayner et al. (2000) confirmed these results with much higher accuracies and also found that the CP spectral index between 1.4 and 4.8 GHz was approximately flat ($\alpha_{mc} = 0.1 \pm 0.3$, where the CP spectral index ($\alpha_{mc}$) is defined as $mc \propto \nu^{\alpha_{mc}}$, with $mc = |V/I|$ defining the degree of CP) for a sample of 12 AGN. Substantial progress has also been made through high spatial resolution CP measurements using VLBI (Homan & Wardle 1999; Homan & Macquart & Fender 2004). For detailed reviews of both the-...
PKS B1934-638 has Stokes V required. The zero-point CP has been set assuming that it is exactly 0%, determined from a source with known CP (e.g., exactly 0%, data in the 4.5 to 6.5 GHz range). Discarded (this only affected some of the linear polarization points with fractional linear polarisation less than 5σ) was PKS B2005-489. Excellent parallactic angle coverage from 1 to 3 GHz has a spectral index of +0.03% at both 1.4 and 4.8 GHz. This means that all CP observations are biased by a fractional CP of equal magnitude and opposite sign to that of PKS B1934-638; although since CP is highly variable this value may have changed since. For our present analysis, we are not overly concerned about potential contamination from this small level of CP, although we do include the CP zero-level of PKS B1934-638 as an additional error in the derived values of $m_c$, where the error in $m_c$ is defined as $\sigma_{m_c}^2 = (\sigma_V/I)^2 + m_{c,1934}^2$, where $m_{c,1934} = 3 \times 10^{-4}$.

3 RESULTS & DISCUSSION

Figure 1 shows the full Stokes properties of PKS B2126–158 from 1.5 to 10 GHz. The total intensity spectrum is shown in Figure 1a, with the dashed line representing a fifth-order polynomial fit to the data. The inverted part of the spectrum from 1 to 3 GHz has a spectral index of $\alpha = +0.945 \pm 0.001$ (by fitting a power-law to the data in this range). A peak flux of $I_{\text{max}} = 1.744 \pm 0.001$ Jy (measured from a parabolic fit to the 4.5 to 6.5 GHz data only). A power-law fit to the steep part of the spectrum at the high frequency band of 8 to 10 GHz found $\alpha = -0.708 \pm 0.003$. The observed levels of Stokes V display a smooth variation across the entire band, with a peak value of $\approx -18$ mJy (9σ) at 6.5 GHz and turning over somewhere between 6.5 and 8 GHz (Figure 1b).

Figure 1. Integrated spectrum of PKS B2126–158 from 1.5 to 10 GHz with data points plotted in 128 MHz intervals: (a) Stokes $I$ in Jy, with 3σ error bars (too small to be visible) (b) Stokes $V$ in mJy, with 3σ error bars (c) degree of circular polarization $m_c \equiv |V|/I$ in per cent, with 3σ error bars (d) degree of linear polarization, $p$, in per cent, with 3σ error bars after correction for Ricean bias ($p < 5\sigma$ data not shown) (e) linear polarization angle ($\Psi$) in degrees, with 3σ errors bars ($\Psi$ data values not shown where $p < 5\sigma$). See Section 2 for definitions of errors. The dashed lines correspond to fifth-order polynomial fits to the data. The solid lines (red) in panel (c) represent power-law fits to the data (Section 3), while in panel (e) the solid lines (red) represent the best-fit Faraday rotation law (see Section 3.2 and Figure 4 for details).
the lowest detected level of CP flux of \( \sim 3 \) mJy is at high significance (15\( \sigma \)). The sign of Stokes \( V \) corresponds to left-circularly polarized emission and does not change across the band. For \( \nu < 6.5 \) GHz, we fit a power-law to the percentage CP \( (\alpha_c) \), finding a CP spectral index \( \alpha_{mc} = +0.60 \pm 0.03 \). For \( \nu > 8 \) GHz, we find \( \alpha_{mc} = -3.0 \pm 0.4 \). Both fits are represented by the solid lines on Figure 1b. We consider these fits as the most robust measurements of the CP spectrum of an extragalactic source to date. The high fractional CP of 0.5 to 1% seen here is uncommon in AGN, with values approaching 1% and greater being very rare (Macquart et al. 2000). Previous measurements of large CP from the intra-day variable source PKS B1519-273 (Macquart et al. 2000), determined a CP spectral index \( \alpha_{mc} = 0.7 \pm 0.3 \) from observations at 1.4, 2.3, 4.8 and 8.4 GHz. Since this is consistent with our observed CP spectrum, below the turnover, it potentially indicates a common generation mechanism in both these sources.

As a check of the reliability of our results we also show the derived spectrum for the Compact, Steep-Spectrum (CSS) source PKS B0252-712 (Tzioumis et al. 2002). This source was observed contemporaneously and exactly the same calibration solutions were applied as for PKS B2126–158 in each band. As is clearly seen in Figure 2 no significant levels of CP are detected. This is not unexpected given that its emission is dominated by a compact, double-lobed structure (Tzioumis et al. 2002, fig. 5). It is also worth noting that, considering the relatively low fractional LP levels of PKS B2126–158, it is not conceivable that the measured Stokes \( V \) is leakage from Stokes \( Q \) and \( U \). This gives us full confidence in the reliability of our CP measurements for PKS B2126–158 as well as its broadband frequency dependence. We note that the classification of this source as a GPS quasar (Stanghellini et al. 1998) has the potential for confusion with GPS galaxies, from which such high CP would be very surprising given that Doppler boosting is not expected to play a significant role. GPS galaxies are an homogenous class of sources consisting mainly of compact symmetric objects in which the integrated emission is dominated by their extended regions (Stanghellini 2003). GPS quasars, on the other hand, can be considered to be intrinsically similar to flat-spectrum radio quasars (FSRQs) that show a core-jet type morphology on milliarcsecond scales. In this case, a small number of components, close to the base of the jet, dominate the radio emission and lead to a turnover in the integrated spectrum due to either synchrotron self-absorption (Maitra et al. 1983) or free-free absorption (Bicknell et al. 1997).

3.1 Spatial location of the emission

PKS B2126–158 has been observed at high angular resolution (~5 mas) with VLBI (Fomalont et al. 2000; Scott et al. 2001; Charlot et al. 2010), showing that the total flux is almost completely dominated by the core with only a small extension of emission to the south. This indicates a potentially very small angle to the line of sight for this source and hence, strong Doppler boosting of the approaching jet emission. Rayner (2000) found an integrated flux of ~1.2 Jy at 4.8 GHz with the ATCA in Oct 1995, while monitoring of this source by Tingay et al. (2002) with the ATCA between 1996 and 2000 found approximately the same flux, with the source exhibiting no significant variability during this time. Fomalont et al. (2000) also found a total flux of ~1.2 Jy from model-fitting 2-D Gaussian components to VLBA observations at 5 GHz in June 1996. From this we can conclude that there is no significant flux on intermediate angular scales for this source and practically all the emission we observe with the ATCA is coming from the compact inner jet regions (i.e. within ~5 mas, which corresponds to a projected linear size of ~40 pc). Therefore, for this particular source, both the Stokes \( I \) and Stokes \( V \) emission we detect is most likely coming from the bright, unresolved VLBI core. This is consistent with the vast majority of VLBI CP observations (Homan & Lister 2006; Vitrishchak et al. 2008) and, importantly, gives us confidence that our CP spectral indices would be the same as those derived if the observations were conducted with the high spatial resolution of VLBI. It

![Figure 2. Integrated spectrum of PKS B0252-712 from 1.5 to 10 GHz with data points plotted in 128 MHz intervals: (a) Stokes \( I \) in Jy, (b) Stokes \( V \) in mJy, (c) degree of circular polarization in per cent. The error bars are plotted in the same manner as in Figure 1. No significant levels of Stokes \( V \) are detected above 5\( \sigma_v \) for this source. Plots of linear polarization are not included as there were no detections above 5\( \sigma_p \). The dashed line in panel (a) corresponds to a fifth-order polynomial fit to the data. The solid lines in panels (b) and (c) are not fits to the data but simply drawn at zero.](image-url)
is important to note that this source appears to have flared around 2009 with its 5 GHz Stokes $I$ flux increasing to its current level of $\sim$1.7 Jy. However, the amount of Stokes $V$ appears to have changed very little, since the decrease in $m_c$ from $\sim$1.4% (Rayner 2000) to $\sim$0.9% at 4.8 GHz can be explained almost purely by the increase in the Stokes $I$ flux alone.

### 3.2 Consideration of the Linearly Polarized Emission

Figure 1 shows the frequency dependence of the linear polarized emission over the same range as the total intensity and circular polarization. We note the low degree of linear polarization ($p \lesssim 0.2\%$) from 4.5 to 6.5 GHz and the surprisingly steep rise toward $p \sim 1\%$ at both ends of the band, as well the non-monotonic distribution of linear polarization angles ($\Psi$) with frequency. Assuming that the linear polarized emission we are coming from the same region of the jet as the CP, then the ratio of $m_c$ to $p$ also reaches surprisingly large values, ranging from $\sim$0.5 to $\sim$10 across our full frequency coverage.

The inverted spectrum of the Stokes $I$ emission from 1.5 to 6.5 GHz (Figure 1a) indicates that the observed emission in these frequency bands originates from a large range of optical depths in the jet. If we consider the most commonly used jet model of Blandford & Königl (1979), then the position of the unity optical depth surface is frequency dependent (i.e. $\tau_{\gamma=1} \propto \nu^{-1}$). Hence, any analysis of the polarized emission from 1.5 to 6.5 GHz is complicated by the fact that the observed emission at different frequencies is likely coming from different regions in the jet. Numerical radiative transfer modelling is required to properly analyse the polarised emission from these regions and we defer such detailed analysis to future work. For the remainder of this paper we conduct a more qualitative analysis, where we will refer to the “optically thick” regime as corresponding to emission at $\nu < 6.5$ GHz and the “optically thin” regime, where the spatial location of the emission does not change with frequency, corresponding to $\nu > 8$ GHz.

In Figure 1c,d the percentage linear polarization ($p$) appears anti-correlated with the percentage CP ($m_c$), so in Figure 3, we plot $p$ versus $m_c$ for each frequency measurement. A Spearman rank correlation coefficient of $-0.8$ quantifies the strong anti-correlation between these two variables, where a correlation coefficient of $-1$ occurs in the case of a perfect anti-correlation. This is the first time such a relation between the LP and CP of an AGN jet has been observed, and strongly supports the action of Faraday conversion of LP to CP. Fitting a power-law dependence to the data gives a best-fit relation $m_c \propto \nu^{-0.24\pm0.03}$ (Fig. 3). Such a dependence has not been predicted in previous theoretical work. However, the degree of LP can also be strongly affected by the frequency dependent effects of Faraday depolarisation as well as optical depth effects, which makes this relation non-trivial to analyse. Separate power-law fits to the $m_c$ ver-
sus $p$ data in the optically-thick and optically-thin regimes

\[ m_{\text{thick}} \propto \nu^{-0.33 \pm 0.04} \quad \text{and} \quad m_{\text{thin}} \propto \nu^{-0.25 \pm 0.05}, \]

respectively. This may lead one to naively suggest that conversion is more efficient in the optically-thin regime; however, it is more likely that different linear polarization characteristics due to optical depth effects are responsible. In any case, the scatter in the data is large and it is premature to draw any definite conclusions about differences between conversion efficiency in the optically thick/thin regimes.

For both the intrinsic CP and Faraday conversion of LP to CP mechanisms, the large CP excess (ratio of CP to LP), noted at the beginning of this section, is not generally expected (e.g. Jones & O'Dell 1977; Valtaoja 1984). The low observed levels of fractional linear polarization are most likely explained by either strong depolarization from internal Faraday rotation and/or large rotation measure gradients in an inhomogeneous external screen. In general, the distribution of Faraday rotating material in the immediate vicinity of AGN jets is not very well constrained. Most studies conclude that the majority of rotating material is contained in a sheath of slower moving, thermal material surrounding the jet (e.g. O'Sullivan & Gabuzda 2003; Broderick & Loeb 2003; Porth et al. 2011, and references therein). Although a significant contribution from unrelated ionized gas clouds, that clearly exist in some sources (Walker et al. 2000), cannot be discounted. Large amounts of Faraday rotation from thermal plasma within jets is generally considered unlikely on energetic grounds (Celotti et al. 1998), and we also consider it unlikely for this particular source (see Section 3.3 for details).

Recent work by Farnsworth et al. 2011 and O'Sullivan et al. 2012 shows that fitting various Faraday rotation models simultaneously to the $Q/I$ and $U/I$ data provides the most robust estimation of RM. However, this implicitly assumes a negligible contribution from conversion of LP to CP. Since the frequency dependence of our Stokes $Q$ and $U$ data is clearly contaminated by the large amount of Stokes $V$ in this source, we revert to the traditional way of finding the RM, by fitting a line to the variation in the linear polarization angle with wavelength squared ($\Delta \Psi = \text{RM} \times \nu^2$), where the change in the linear polarization angle, $\Delta \Psi$, gives $\text{RM}$ in the linear polarization angle with wavelength squared way of finding the RM, by fitting a line to the variation of $V$ of Stokes $Q$ to $V$ and $U$ to $U$ data in the optically-thick and optically-thin regimes gives $m_{\text{thick}} \propto \nu^{-0.33 \pm 0.04}$ and $m_{\text{thin}} \propto \nu^{-0.25 \pm 0.05}$, respectively. This may lead one to naively suggest that conversion is more efficient in the optically-thin regime; however, it is more likely that different linear polarization characteristics due to optical depth effects are responsible. In any case, the scatter in the data is large and it is premature to draw any definite conclusions about differences between conversion efficiency in the optically thick/thin regimes.

3.3 Circular polarization generation mechanism

Through our measurements, there are several fundamental aspects relating to the CP generation mechanism on which we can comment. Firstly, we can conclusively rule out intrinsic CP from a homogeneous source region as the dominant source of CP, since the spectrum does not follow the expected frequency dependence of $m_{\text{c}} \propto \nu^{-1/2}$ in the optically-thin regime (Legg & Westfold 1968) and Stokes $V$ does not change sign near the Stokes $I$ turnover frequency (Melrose 1972). For conversion of LP to CP in a homogeneous source, Kennett & Melrose (1998) predict $m_{\text{c}} \propto \nu^{-1}$ for a co-spatial relativistic and cold plasma or $m_{\text{c}} \propto \nu^{-3}$ for purely relativistic plasmas. In the optically thin regime (i.e. $\nu > 5 \text{ GHz}$), we find $m_{\text{c}} \propto \nu^{-3.1 \pm 0.4}$. This strongly supports conversion of LP to CP by the relativistic particles and magnetic field within the jet as the dominant CP generation mechanism in this source (and rules out any significant contribution from thermal plasma within the jet). However, we cannot determine the exact jet composition from this model, since such a dependence of $m_{\text{c}}(\nu)$ can occur in a normal plasma (relativistic electrons and protons) or in a pure pair-plasma (relativistic electrons and positrons).

The frequency dependence of $m_{\text{c}}$ below the turnover (from 1.5 to 6.5 GHz) is more difficult to analyse than the dependence above the turnover, because of the need for polarized radiative transfer simulations to accurately model the physical properties of the jet. Such simulations were done by Jones & O'Dell (1977) and Jones (1983), predicting that both conversion and synchrotron emission can contribute to the observed CP. In the case of inhomogeneous source

\[ 2 \text{ AGN jets are considered to be effectively charge-neutral, with roughly equal numbers of relativistic electrons and protons (or positrons) flowing outwards (Bezegman et al. 1984).} \]
regions, they found that conversion was the dominant process, with the CP strongest near the optically thick core at the base of the jet. The fact that our observed $m_\perp$ peaks near the frequency at which the Stokes $I$ emission turns over is a strong indication that conversion is the dominant generation mechanism for this source. Furthermore, we do not observe a 90° LP angle flip, when going from the optically thin to optically thick regime across the turnover.

This is also consistent with the results of Jones & O’Dell (1973) and Kennett & Melrose (1998), who described in detail by Gabuzda et al. (2008), is very plausible. In such a model, the CP sign can be used to infer the direction of the accretion flow and/or black-hole spin. In the optically thin regime, the linear polarization vector generated from LP in a jet with a helical magnetic field, as one would expect $V \propto \sin(c_\perp R M / \nu^3)$ in the optically-thin regime (Macquart et al. 2009). Fitting this relation to our data from 8 to 10 GHz, we find $R M = 661 \pm 127 \text{ rad m}^{-3}$, which allows us to estimate a jet magnetic field strength $\sim 30 \text{ mG}$ assuming a jet width of 1 pc. We consider this magnetic field strength reasonably robust since changing the jet width by an order of magnitude only changes the magnetic field estimate by a factor of $\sim 1.8$.

Using standard synchrotron theory and assuming that there is a single jet feature dominating the emission, we can estimate the angular size of the emission region using the equations listed in Marscher (1983). At unity optical depth, the magnetic field strength can be estimated using

$$B = 10^{-5} b(\alpha) S_m^{-2} \nu_b^2 \theta^4 (1 + z)^{-1} \delta \ [\text{G}]$$

where $S_m = 1.744 \text{ Jy}$ is the measured flux at the turnover frequency of $\nu_m = 5.7 \text{ GHz}$, $\theta$ is the angular size of the emission region in milli-arcseconds, $b(\alpha) \sim 3.5$ (Marscher 1983), $z$ is the redshift and $\delta$ is the Doppler boosting factor. Using $B \sim 30 \text{ mG}$ and $\delta = 14$ (Ghisellini et al. 2010), we find $\theta \sim 0.6 \text{ mas}$. Importantly, this is consistent with our assumption that the emission is dominated by a single, compact component near the base of the jet. Furthermore, we can predict that observations with the VLBA at 22 GHz and higher should be able to resolve this emission feature. The formulation of Marscher (1983) also allows us to independently compare the energy density in the relativistic electrons ($U_{e\gamma}$) with the energy density in the magnetic field ($U_B$). We find $U_{e\gamma} \sim 3 U_B$, showing that the equipartition magnetic field estimated through the RRM formulation is roughly consistent with the well-tested synchrotron theory. Intrinsic CP from synchrotron emission ($m_{\perp \text{int}}$) is likely to contribute a small amount to the total observed CP level for a magnetic field strength of $\sim 30 \text{ mG}$. However, it is interesting to note that even if the jet magnetic field was completely uniform, which is highly unlikely given the low observed levels of LP, then the intrinsic CP generation mechanism would still not be able to reproduce the observed CP of $\sim 1\%$ at 5.7 GHz ($m_{\perp \text{int}} \sim \gamma^{-1} \sim 0.7\%$, where $\gamma = [\nu(1+z)/2830]^{1/2}$ is the Lorentz factor of the radiating electrons).

In order to test the Faraday rotation-driven and magnetic-twist conversion models, we use the relevant equations (e.g., Wardle et al. 1998; Ruszkowski & Begelman 2002; Wardle & Homan 2003; Homan et al. 2009 and references therein) describing the relationship between the linear and circular polarisations in a partially ordered field. For small optical depths, we have

$$m_\perp \sim \frac{1}{6} \nu^2 \tau_F \tau_C,$$

where $\tau_F$ is the Faraday rotation depth and $\tau_C$ is the Faraday conversion depth of the jet, which are described by the equations (ignoring some factors of order unity)

$$\tau_F \sim f_{\perp} \gamma^{2} \frac{\ln \gamma_{\min}}{\gamma_{\text{min}}^{3}},$$

\[ \text{and} \]

$$\tau_C \sim f_\parallel \gamma^{2} \frac{\ln \gamma_{\min}}{\gamma_{\text{min}}^{3}},$$

where $f_\perp$ and $f_\parallel$ are the fractional polarization of the electric fields in the parallel and perpendicular components, respectively.
where $\gamma_{\text{min}}$ is the lower cutoff in the relativistic particle energy spectrum and $f_u$ is the fraction of uniform magnetic field along the jet axis. To generate $\tau_B \sim 1000$ rad m$^{-2}$ at unity optical depth ($\tau = 1$), where we have $\nu \sim 5.7$ GHz, $B \sim 30$ mG and $\delta \sim 14$. Such a large Faraday depth model is inconsistent with our observations since we find $\tau_F = -6 \pm 2$ (using the observed RM of $-239 \pm 87$ rad m$^{-2}$ in the frequency range from 4.5 to 6.5 GHz). We note that the simple scalings listed above do not hold in all cases, therefore, more detailed simulations are required before discounting such a model. For example, significant levels of CP can occur from anisotropic turbulence in the jet, where the anisotropy is created from a net poloidal magnetic flux, and conversion of LP to CP can occur over very small length scales in the jet due to very large internal Faraday rotation \citep{Ruszko02, Beckert02}. In this model, significant depolarisation of the linear polarisation can occur, resulting in the CP exceeding the LP in some cases. For example, \cite{Ruszko02} were still able to produce a CP excess of $\sim 5\%$ in their model for Sgr A* with $\gamma_{\text{min}} = 3$ and no addition of cold electrons to the jet.

A second scenario worth considering is where some of the Faraday rotation is external to the jet and variations in the RM (\sigma_{\text{RM}}) about the mean observed value cause depolarization of the linearly polarized emission. Assuming random fluctuations in the magnetic field and/or electron density external to the jet leads to depolarisation described by $p/p_i = e^{-2\sigma_{\text{RM}}^2}$ \citep{Burn66}, where $p_i$ is the intrinsic degree of linear polarization in the jet. Using $p_i \sim 3\%$, which we consider typical of a synchrotron self-absorbed VLBI core \citep{Lister05}, we require $\sigma_{\text{RM}} \sim 400$ rad m$^{-2}$ to observe $p \lesssim 0.2\%$ at 5.7 GHz. While such a seemingly large dispersion in RM may be surprising, large spatial variations in RM of order of thousands of rad m$^{-2}$ are not uncommon in the innermost regions of AGN jets (e.g.,\cite{Attridge03, Aligabi11, Aligabi13}). We can now obtain $m_e \sim 1\%$ more easily from Faraday conversion of the fraction linear polarisation, $p_i \sim 3\%$, within the jet, with $f_u = 0.1$ and $\gamma_{\text{min}} = 7$. The Faraday depth of the jet is now approximately a factor of 2 greater than the observed value, however, a small number of reversals of the line-of-sight magnetic field through the jet could bring this in line with the observations. In summary, this model remains consistent with the observations assuming the CP is generated through Faraday rotation-driven conversion by the low energy end of the relativistic electron energy spectrum and some depolarisation of the LP also occurs external to the jet.

The third main case to consider is one in which the internal Faraday rotation is completely suppressed due to the jet being composed of equal numbers of electrons and positrons \citep{Enßlin03}. The observed CP must then be generated through conversion from LP due a systematic twist in the jet magnetic field (e.g., a helical magnetic field), with the process being mathematically identical to Faraday rotation-driven conversion at a single frequency (cf \cite{Enßlin03}). Such a model is difficult to constrain since all the observed Faraday rotation (and frequency-dependent depolarisation of the LP) must be external to the jet. For PKS B2126–158, we found the observed RM scales with frequency in a similar manner to what is expected for Faraday rotation internal to the jet (Section 3.2). Therefore, in this case the external RM would most likely come from a mixing layer/sheath surrounding the jet where the product $n_e B$ scales in the same manner with distance from the base of the jet as expected from internal Faraday rotation. Overall, the frequency dependent properties of the CP is one of the main aspects in which this model can differ observationally from the Faraday rotation-driven conversion case. For example, in the case of a helical magnetic field the magnitude of the CP depends only on $\tau_C$, and is therefore expected to decrease more slowly with increasing frequency than in the Faraday rotation-driven case, which depends on the product $\tau_F \tau_C$ \citep{Enßlin03, Homan09}.

The observed steep frequency dependence of $m_e$ above the turnover in Stokes $I$ (from 8 to 10 GHz) means that there are little or no thermal electrons mixed in with the relativistic plasma in the jet, as already discussed. Additional observational constraints and detailed jet simulations are required to determine the fraction of relativistic electrons to positrons and protons in the jet. Below the turnover (from 1.5 to 6.5 GHz), we attempt a qualitative description of the frequency dependence of $m_e$ using a simple conical jet model \citep{Blandford79, Wardle03}. Considering conservation of magnetic flux in such a model, the uniform component of the magnetic field along the jet axis ($B_z$) will decay as $r^{-2}$, while the fluctuating component of the field ($B_{rms}$) will decay as $r^{-1}$ for a conical jet in equipartition (e.g.,\cite{Ruszko02}). Using Eqn. 3, we see that $\tau_F \propto \gamma^2 B_z/B_{rms}$ and $\tau_C \propto \ln \gamma$ for relativistic electrons radiating at a particular frequency, $\nu \propto \gamma^2 B_{rms}$. For a constant or slowly changing $\gamma$ along the jet, $\tau_C \sim$ constant, while $m_e \propto \nu \propto n e B_z/B_{rms} \propto \nu$. Therefore, in the optically thick regime, the degree of CP will increase with increasing frequency as observed from 1.5 to 6.5 GHz. Our fitted result of $m_e \propto \nu^{-0.6 \pm 0.03}$ could be obtained for slight variations in these scalings. For example, if the fluctuating component of the magnetic field falls off slightly faster with distance from the base of the jet (e.g., $m_e \propto \nu^{-0.8}$ for $B_{rms} \propto r^{-1.2}$),

Recently, \cite{Homan09} studied the full radio polarization spectra of the quasar 3C 279 ($z = 0.5362$) at high spatial resolution with the Very Long Baseline Array (VLBA). They used numerical radiative transfer simulations to test various jet models for production of CP that also remained consistent with the LP and total intensity emission. They found the Stokes $I$ core flux of 3C 279 ($z = 0.5362$) had an inverted spectrum with $I \propto \nu^{-0.9}$ from 8 to 24 GHz (similar to PKS B2126–158 from 1 to 3 GHz) while the fractional CP reached $\sim 1\%$ at 24 GHz with $p \sim 2$ to $3\%$. Through an extensive parameter-space search, they found a model consistent with all the observed data that implies the CP is most likely generated from a combination of intrinsic CP and conversion from Faraday rotation internal to the jet. From figure 10 of \cite{Homan09}, we see that the expected CP varies from $\sim 0.5\%$ at 8 GHz to $\sim 1\%$ at 24 GHz leading to a CP spectral index of $\alpha_{m_e} \sim 0.6$. This is consistent with our measured value of $\alpha_{m_e} = 0.60 \pm 0.03$ from 1.5 to 6.5 GHz.
(or ~6 to 28 GHz in the rest frame of PKS B2126–158). The application of similar radiative transfer simulations to the jet emission properties of PKS 2126–158 is required to determine if the CP generation mechanism is indeed similar to that of 3C 279. We also need to understand why such large fractional CP is generated in these sources compared to the rest of the radio-loud AGN population, which typically have $m_c \lesssim 0.3\%$ (Homan & Lister 2006).

4 CONCLUSIONS

From broadband radio spectropolarimetric observations with the Australia Telescope Compact Array (ATCA), we have obtained full-Stokes measurements of the quasar, PKS B2126–158, from 1 to 10 GHz. We find that the Stokes $I$ spectrum has a peak flux of $I_{\text{max}} \sim 1.7$ Jy at a turnover frequency $\nu_0 \sim 5.7$ GHz with an inverted spectral index of $\alpha = +0.945 \pm 0.001$ below the turnover and a steep spectral index $\alpha = -0.708 \pm 0.003$ above the turnover. Left-circularly polarized emission is detected at high significance across the entire band. The measured Stokes $V$ has a consistent sign and varies smoothly across the band, with a maximum Stokes $V \sim -18$ mJy at 6.5 GHz ($m_c \sim 1\%$), before the spectrum turns over somewhere between 6.5 and 8 GHz. Our detection exhibits the same sign as found 15 years ago by Rayner (2000), who obtained $V/I \sim -1.4\%$ at 4.8 GHz.

From comparison of the integrated flux with high spatial resolution VLBI images, we conclude that there is no significant amount of flux on intermediate angular scales and that effectively all the emission comes from the compact inner jet regions (on scales < 5 mas). Hence, our fractional linear polarization ($p$) and circular polarization (CP) data should be equivalent to that obtained from VLBI images at the same frequencies. The $V$ is clearly anti-correlated with the $CP$, with the degree of CP $m_c \propto P^{-0.24 \pm 0.03}$, where $m_c \equiv |V|/I$. This is the first time such a relation has been observed and clearly indicates the action of Faraday conversion of LP to CP within the jet.

By fitting a power-law to the frequency variation in the degree of CP above the turnover, we find a very steep CP spectral dependence, $m_c \propto \nu^{-3.0 \pm 0.4}$, which is consistent with the prediction of $m_c \propto \nu^{-3}$ for conversion of linear polarization (LP) to CP by purely relativistic particles and magnetic fields within the jet (i.e., no thermal plasma within the jet). Below the turnover we find $m_c \propto \nu^{+0.6 \pm 0.03}$. The increase of $m_c$ with frequency in the optically thick regime is easily understood considering the frequency-dependent location of the emission in which higher frequency observations probe further upstream in the jet where the uniform component of the magnetic field is stronger and, hence, the amount of $m_c$ due to both Faraday conversion and intrinsic CP is larger.

Overall, our results conclusively favour Faraday conversion of LP to CP within the jet as the dominant CP generation mechanism in this source. We are unable to uniquely constrain whether the conversion is achieved by Faraday rotation within the jet dominated by the low energy end of the relativistic electron energy spectrum, or by a change in the orientation of the perpendicular component of a vector-ordered magnetic field through the jet (e.g. a helical magnetic field). Three different scenarios are discussed:

1. Very large amounts of internal Faraday rotation could naturally produce the large CP-to-LP ratios of 0.5 to 10 across our observed frequency range, but this appears inconsistent with our RM measurements.

2. Considering our measured RM as being composed of some internal and external components, we can obtain the observed levels of CP at $\tau \sim 1$ due to Faraday rotation-driven conversion, with the fraction of uniform magnetic field along the jet axis $f_u = 0.1$ and a low energy cut-off in the relativistic electron energy spectrum of $\gamma_{\text{min}} = 7$.

3. If all the observed Faraday rotation is external to the jet, then we require large spatial gradients in the external RM distribution to strongly depolarize the LP emission. Conversion of LP to CP within the jet is then achieved solely by a systematic twist in the magnetic field through an electron-positron jet.

The observed low levels of LP and frequency dependence of the magnitude of the RM favour a model in which there is some contribution of internal Faraday rotation. This leads us to suggest that Faraday rotation-driven conversion by the low energy end of the relativistic electron energy spectrum, in a mainly electron-proton jet with ~10% uniform magnetic flux along the jet axis, as the most likely explanation for the observed levels of CP in this source. Future work requires detailed numerical, polarized, radiative transfer simulations in conjunction with realistic internal and external Faraday rotation models to consistently explain the full-Stokes emission from PKS B2126–158 and its variation across the entire observed frequency range.

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