STRONG, VARIABLE CIRCULAR POLARIZATION IN PKS 1519−273

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ABSTRACT

We report strong variability in the circular and linear polarization of the intraday variable source PKS 1519−273. The circular polarization varies on a timescale of hours to days at frequencies between 1.4 and 8.6 GHz, and is strongly correlated with variations in the total intensity at 4.8 and 8.6 GHz. We argue that the variability is due to interstellar scintillation of a highly compact (15−35 μas) component of the source with −3.8% ± 0.4% circular polarization at 4.8 GHz. We find that no simple model for the circular polarization can account for both the high magnitude and the frequency dependence in PKS 1519−273 at centimeter wavelengths.

Subject headings: BL Lacertae objects: individual (PKS 1519−273) — polarization — radiation mechanisms: nonthermal — scattering

1. INTRODUCTION

Circular polarization (CP) in extragalactic sources is very small, typically 0.05% to 0.1% of the total source flux density (e.g., Roberts et al. 1975; Seaquist et al. 1974; Weiler & de Pater 1983) and sometimes variable (Komesaroff et al. 1984). Recent measurements of CP in extragalactic sources have rekindled debate as to its characteristics and origin. Wardle et al. (1998) detected CP in 3C 279 and attributed it to the presence of a relativistic pair plasma. New evidence has emerged that Sgr A*, the AGN-like object at the core of our own Galaxy, is also weakly circularly polarized (Bower, Falcke, & Backer 1999; Sault & Macquart 1999).

We present Australia Telescope Compact Array (ATCA) measurements of the timescale and magnitude of the variability of the CP in the extragalactic, intraday variable (IDV) BL Lac object, PKS 1519−273 (White et al. 1988). PKS 1519−273, at Galactic coordinates l = 339°5, b = 24°5, is identified with a mv = 18.5 star-like object with a featureless optical spectrum. The lower limit on its redshift is z = 0.2 (Veron-Cetty & Veron 1993). PKS 1519−273 is a compact high brightness temperature radio source (Linfield et al. 1989). The ATCA IDV Survey data shows strong IDV (Kedziora-Chudczer 1998) and IDV of the total and polarized flux densities at GHz frequencies has been found during each of the five epochs of ATCA observations over the past 7 yr.

PKS 1519−273 has not been seen to exhibit IDV at either optical (Heidt & Wagner 1996) or mm wavelengths (Steppe et al. 1988, 1995). However, it does have a high degree (5%−12%) of variable optical linear polarization (Impey & Tapia 1988). PKS 1519−273 is a weak, soft X-ray source with a flux density at 1 keV of 0.39 μJy (Urry et al. 1996). Its γ-ray energy output is less than 0.7 × 10−7 photons cm−2 s−1 for energies E > 100 MeV (Fichtel et al. 1994).

2. OBSERVATIONS AND RESULTS

We base our present report on PKS 1519−273 on the data obtained with ATCA over 5 days starting on September 9. Data were collected simultaneously for two frequencies centered on either 1.384 and 2.496 GHz, or 4.800 and 8.640 GHz each with a 128 MHz bandwidth. To ensure high-quality amplitude and phase calibration we frequently observed both the standard primary flux density calibrator, PKS 1934−638, and a secondary calibrator, PKS 1514−241. The primary calibrator was used to determine accurately the flux density scale and the instrumental polarization leakages (e.g., Sault, Killeen, & Kesteven 1991). The total and polarized flux density light curves of PKS 1519−273 are presented in Figure 1. The circularly polarized emission is unresolved on all ATCA baselines and is strongly variable at 4.8 and 8.6 GHz. Comparison of the 2.5, 4.8 and 8.6 GHz Stokes V measurements for PKS 1519−273 and the strong calibrator source PKS 1514−241, extensive testing and consistency checks demonstrate that the observed CP and its variations are not instrumental effects.

The most striking features of the 4.8 and 8.6 GHz light curves in Figure 1 are the exceptionally high level of CP and the large amplitude variability in all four Stokes parameters. The fractional variability of both the circularly and linearly polarized flux density exceeds that of the total flux density. The high degree of correlation between the fluctuations in I and V (see Figs. 1 and 2) suggests that the mechanism of variability of the CP is strongly related to that in I. Comparison of the fluctuations in V with those in I implies that, although the overall CP is only ≳1%, the CP of the variable component, ΔV/ΔI, is −2.4% ± 1.3%, −3.8% ± 0.4% and −2.6% ± 0.5% at 2.4, 4.8 and 8.6 GHz respectively (see Figs. 2 and 3). The CP is weaker, less than 1.3% at 1.4 GHz and its variability is less well-established.

3. DISCUSSION

3.1. Scintillation

We attribute the short-timescale variability of this source to Interstellar Scintillation (ISS) in our Galaxy. ISS has already been invoked to explain radio source IDV (Heeschen & Rickett 1997), including the rapid variability of PKS 0405−385 (Kedziora-Chudczer et al. 1997). If intrinsic to the source, the total intensity variations observed at 4.8 GHz imply a brightness temperature of T_b ≳ 3 × 1017 K for z ≳ 0.2, based simply on light travel times. However, assuming that the variations are intrinsic implies a source size that is necessarily sufficiently small to
Fig. 1.—Variability of PKS 1519−273 in the total intensity (I), CP (V), and magnitude of the linear polarization (P), for the four bands of the ATCA over 5 days. Each point represents a 10 minute average and is plotted with 1 $\sigma$ error bars. Fluctuations in $I$ and $V$ are strongly correlated ($r = 0.90$ at 4.8 GHz and $r = 0.80$ at 8.6 GHz).

exhibit variability due to ISS (Rickett et al. 1995). This suggests that an explanation based on ISS should be sought first.

The increase in modulation index (the rms normalized by the mean intensity), shown in Fig. 3, and the short variability timescale from 8.6 to 4.8 GHz, shown in Fig. 1, are consistent with scintillation in the regime of weak scattering (e.g., Narayan 1992), while the decrease in modulation indices and the increasingly longer variability timescales from 4.8 to 1.4 GHz are characteristic of refractive scintillation.

Assuming that the density inhomogeneities in the ISM are located on a thin screen, the refractive scintillation at 1.4 GHz may be used to place a constraint upon the distance to the scattering screen. The physical extent of the scattering disk at 1.4 GHz is the product of the long-period, refractive variability timescale, $t_{1.4} \gtrsim 4$ days (see Fig. 1), and the scintillation speed, $v$, of order 50 km s$^{-1}$ (see Rickett et al. 1995). VSOP observations at 1.7 GHz indicate that the source is unresolved, so we assume an angular size of no more than 0.3 mas. This implies an observer-screen distance of $D \gtrsim 390(v/50 \text{ km s}^{-1})(t_{1.4}/4 \text{ days}) \text{ pc}$, or 390 pc in the present case.

Having obtained a lower limit to the distance to the scattering screen, we may constrain the angular diameter of the source from the scintillation parameters in the weak scattering regime where the scattering is quite sensitive to source size effects. The scintillation timescale of $\sim 12 \text{ hr}$ at 4.8 GHz can be explained either in terms a scattering screen at large distance ($> 15$ kpc), or by a partially resolved source. For weak scattering, the source is resolved if the

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4 See http://www.vsop.isas.ac.jp/general/pr/1519-273.gif.
angular diameter of the source, $\theta_S$, exceeds the angular diameter of the first Fresnel zone $\theta_F = (kD)^{-1/2}$, where $k$ is the wavenumber. The scintillation timescale is then $t_{\delta} \approx \theta_S D/v$ for $\theta_S > \theta_F$ (Narayan 1992). A screen in our own Galaxy implies $D < 15 \text{ kpc}$, so the source must be partially resolved. Assuming the asymptotic results of weak scat-

ering to be valid between the weak and strong scattering regimes, the scintillation timescale then yields an estimate of the intrinsic angular source size of

$$\theta_S \approx 14.4 \left(\frac{t_{4.8}}{12 \text{ hr}}\right) \left(\frac{v}{50 \text{ km s}^{-1}}\right) \left(\frac{D}{1 \text{ kpc}}\right)^{-1} \mu\text{as}.$$  \hspace{1cm} (1)

For a scintillating source of flux density $I_0$, the rms fluctuation is $I_{\text{rms}} = I_0 m(\theta_S)$, where $m(\theta_S) = (kD\theta_S^2)^{1/2}$ is the modulation index expected for a source of size $\theta_S > \theta_F$ (e.g., Narayan 1992), and we have assumed that 4.8 GHz is near the transition frequency between weak and strong scat-
ttering. Given $I_{\text{rms}} = 0.11 \text{ Jy}$ and with the derived angular size of the scintillating component of the source, we estimate $I_0$ and derive its brightness temperature:

$$T_b \approx 2.0 \times 10^{14} \left(\frac{D}{1 \text{ kpc}}\right)^{17/12} \left(\frac{t_{4.8}}{12 \text{ hr}}\right)^{-5/6} \times \left(\frac{v}{50 \text{ km s}^{-1}}\right)^{-5/6} \text{K}.$$  \hspace{1cm} (2)
Using the limit of the distance to the scattering screen, the maximum possible angular size of the source for \( t_{4.8} = 12 \) hours and \( v = 50 \text{ km s}^{-1} \) is 37 \( \mu \text{as} \), the minimum brightness temperature is \( T_B = 5 \times 10^{13} \text{ K} \), consistent with incoherent synchrotron emission subject to relativistic beaming with a Doppler boosting factor \( \delta \gtrsim 200(1 + z) \) (Readhead 1994).

However, if the CP observed at 4.8 GHz is entirely due to the variable component, we may further constrain \( T_B \). From Figure 2 we have \( I_o = 0.35 \pm 0.04 \text{ Jy} \), implying \( m(\theta_i) \approx 0.32 \) (consistent with the modulation index observed in \( V \)) and hence an angular size of \( 9.8(1 + z)^3 f_o(8.6 \text{ GHz}) \text{ rad m}^2 \) to explain the \( -2.6\% \) CP at 8.6 GHz, where we write \( f_o(8.6 \text{ GHz}) = |U_0(8.6 \text{ GHz})/(8.6 \text{ GHz})| \). For this lower limit, \( \lambda^2 \text{RRM} \) will vary by 0.88/\( f_o(8.6 \text{ GHz}) \) rad across 64 MHz bandwidth at 1.4 GHz and 0.08/\( f_o(8.6 \text{ GHz}) \) rad at 2.5 GHz. We searched for frequency-dependent variations in CP at all four frequencies by selecting two adjacent 32 MHz sub-bands at each frequency. None were found. Although the Faraday rotation (RRM \( \approx 69 \text{ rad m}^2 \)) across the band was clearly detected at 1.4 and 2.5 GHz, the variations in CP between sub-bands were less than 4% and 0.8% at these frequencies respectively. This result appears inconsistent with the derived lower limit on RRM, although the null result at 1.4 GHz may result from an absence of CP in the scintillating component (which in turn implies \( |U_0(1.4 \text{ GHz})| \approx |V(1.4 \text{ GHz})| < 0.01 \text{ at } 1.4 \text{ GHz} \)).

The fact that all detections of the CP are of same sign also argues against this model. If (1) \( V \) does not change sign at any frequencies intermediate to those of our measurements (i.e., the spectrum is well-sampled) and (2) \( U_0 \) does not change sign in the range 1.4—8.6 GHz, then equation (3) implies \( \lambda^2 \text{RRM} < 2\pi \) for all frequencies above 1.4 GHz (even if \( V(1.4 \text{ GHz}) \), whose sign is uncertain, is positive). At 1.4 GHz one then has \( | \text{RRM} | < 6.2 \times 10^3 (1 + z)^3 \text{ rad m}^2 \), requiring \( f_o(8.6 \text{ GHz}) \gtrsim 100\% \) to be consistent with the lower limit on RRM obtained above. While difficult to exclude entirely, we therefore conclude that the production of CP by a pair-dominated plasma is implausible.

Polarization conversion may also occur in a medium containing a mixture of cold and relativistic pair plasma, in which case the fractional CP varies as \( m \propto v^{-1} \) (Pacholczyk 1973). This model appears implausible in light of the observed \( \rho^{6.7 \pm 1.3}_{\text{SSA}} \) frequency dependence of the CP from 1.4 to 4.8 GHz.

The presence of several distinct subcomponents may alter the spectral properties of the observed CP. However, the scintillation characteristics argue against the existence of multiple circularly polarized components, each with distinct \( U_0 \), RRM, and \( \gamma \). The presence of multiple components with different \( V/I \) would lead to substructure in the light curve of \( I \) compared to the light curve of \( I \) as the scintillation selectively amplifies and deamplifies parts of the source differently. This would result in a loss of correlation between \( V \) and \( I \), particularly at 4.8 and 8.6 GHz, where the scintillation is most sensitive to small-scale structure. This is not observed in Figure 1 where the correlation coefficients are close to unity. However, it is more difficult to ascertain the presence of substructure in the variability at 1.4 and 2.5 GHz due to the long timescale of the fluctuations.

Jones & O’Dell (1977a, 1977b) presented a model for the CP of inhomogeneous synchrotron sources, incorporating optical depth effects, mode coupling and mode conversion due to the birefringence of the plasma. Below the self-absorption turnover frequency, \( v_{\text{SSA}} \), mode coupling dominates, and the CP is typically less than 0.05%, and certainly not more than 2%. Mode conversion dominates above \( v_{\text{SSA}} \).
with the CP as high as 10% near $v_{SSA}$, and decreasing to less than $10^{-3}$ at frequencies a decade above $v_{SSA}$. This model is viable only if $v_{SSA}$ is within a factor $\sim 1.4$ of the frequency at which the high (3.8%) CP was observed, at 4.8 GHz. This is difficult to verify as we do not know the intrinsic spectrum of the scintillating component and the frequency range of our observations is limited.

4. CONCLUSION

The variability detected in PKS 1519—273 in all four Stokes parameters at frequencies from 1.4 to 8.6 GHz is remarkable but has a natural interpretation in terms of ISS. The scintillation properties at 4.8 GHz constrain the brightness temperature of the scintillating component to $T_b \leq 5 \times 10^{13}$ K, although there is strong evidence to suggest it may be as high as $6 \times 10^{14}$ K. Comparison of the fluctuations in $I$ and $V$ imply that this component is exceptionally highly circularly polarized at 8.6 and 4.8 GHz. Simple applications of synchrotron theory and models of circular repolarization encounter difficulties with the spectral behavior and magnitude of the CP. The strong correlation between the fluctuations in $I$ and $V$ at 4.8 and 8.6 GHz and the high sensitivity of the scintillation to source structure at these frequencies argue against a complex source, with different $V/I$ in each component. Inclusion of effects due to small-scale inhomogeneity, mode coupling and optical depth effects may reproduce the observed characteristics of the CP. However, this model is only viable if the frequency at which the source is observed to become optically thin is in the range $3.4$ GHz $\leq v \leq 6.7$ GHz. This possibility is presently difficult to confirm. Even if correct, the puzzle remains as to why so few sources exhibit such high levels of CP.

Finally, in light of the extremely high brightness temperature of PKS 1519—273, we advance the possibility that the observed emission is not due to synchrotron emission at all and that high CP may be a characteristic of a new emission mechanism.

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