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On the Possible Origin of Optical Circular Polarization in Blazars

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Abstract The evidence is corroborating according to which blazar-type sources may show a substantial degree of circular polarization (CP) even at high frequencies (i.e. well in the optically-thin regime). Recent high resolution observations of the quasar 3C279 with the FORS polarimeter at the ESO-VLT for example, indicate a variable, optical circular polarization occasionally exceeding 1%. Here we present an analysis of possible scenarios for the origin of optical CP in 3C279 and assess their plausibility given the observational constraints.

Key words: polarization — radiation mechanisms: general — galaxies: active — quasars: individual: 3C279

1 INTRODUCTION

In the extragalactic field, the term 'blazar' has been introduced to define those variable, radio-loud Active Galactic Nuclei (AGN), whose non-thermal continuum spectra are dominated by relativistically beamed synchrotron and inverse Compton emission from their inner jets viewed almost face-on. In recent years, radio polarimetric studies of blazar jets have attracted attention by potentially offering a powerful tool for the diagnosis of the underlying plasma composition. Wardle et al. (1998) for example, have argued that circular polarization (CP) of the order of 1% measured in the radio regime for the quasar 3C279 is caused by Faraday conversion from linear to circular polarization in a mainly (e^+e^-) pair-dominated plasma. While is was shown later on that this conclusion is not as strong as initially thought, since different sets of microscopic parameters could lead to the same macroscopic outcome (e.g., Ruszkowski & Begelman 2002), the analysis of CP is still found to provide important constraints on the intrinsic plasma parameters and may thus be very helpful in assessing the plausibility of different theoretical emission models. In general, strong CP signals in the radio regime are usually associated with the most compact features in AGN, i.e. with the compact components in the core (Rayner et al. 2000). In the case of 3C279 and 3C273 for example, the radio CP signal seems to be related to a new component emerging from the optically thick base of the inner jet/core (Wardle & Homan 2001).

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2 OPTICAL CIRCULAR POLARIZATION (CP) IN BLAZARS

2.1 Previous observational evidences

While significant radio CP, usually with a degree $m_c = |V|/I \lesssim 1\%$, has been established for many AGN (e.g., Roberts et al. 1975; Rayner et al. 2000; Homan et al. 2001), the situation is quite different in the optical regime: So far, observational evidence for optical CP in blazars has been reported only for a few sources, including 3C66A and OJ 287 (Takalo & Sillanpää 1993), PKS 0422+004 and PKS 0735+178 (Valtaoja et al. 1993), and PKS 2155-304 (Tommasi et al. 2001). However, most of these detections were only marginally significant.

2.2 FORS observations of 3C279

The situation has been improved recently due to high-resolution observations of the blazar 3C279 with the FORS 1 (Focal Reducer Spectrograph) instrument at the first unit telescope of the ESO VLT. [1] Based on linear and circular spectropolarimetry, performed in an alternating way during several epochs in 1999 and 2000, strong support for significant CP in the optical regime has been found. A first data analysis has established the following trends (cf., Wagner et al. 2000; Wagner & Mannheim 2001): **(1)** The degree of optical CP is variable on the timescale of several days and occasionally exceeds 1%. **(2)** The degree of optical linear polarization (LP) and the degree of optical CP appear to be anti-correlated: During a state of low total intensity and low LP (i.e., low I,U,Q state, where I, U, Q, V denote the usual Stokes parameters, cf. Kennett & Melrose 1998 for a definition), the degree of CP is $m_c \sim 1.2\%$ (when corrected for dilution). In a state of higher total intensity (i.e., high I,U,Q state) the degree of CP is of order $m_c \sim 0.1\%$.

3 POSSIBLE SCENARIOS FOR THE ORIGIN OF OPTICAL CP IN 3C279

In the following, we present a preliminary analysis of possible scenarios for the origin of optical CP with $m_c \sim 1\%$ in 3C279. In general, at least ten different scenarios may be distinguished. We will first concentrate on relativistic jet scenarios (i.e. points $1-7$ below), where the relevant comoving frequency can be much smaller due to Doppler boosting, and then focus on scenarios associated with the non-relativistic surrounding:

1. Intrinsic CP: Synchrotron radiation itself is characterized by a small degree of intrinsic CP $m_{c0} \propto \nu^{-1/2}$ (e.g., Melrose 1971). For a power law distribution of emitting particles with power index β in a uniform magnetic field, the fractional degree of CP in the optically thin case becomes $m_{c0} = (1-2f)\,g(\beta)\,\cot\theta'\,(\sin\theta')^{1/2}\,(\Omega_0/\nu')^{1/2}$, where θ' is the angle between the magnetic field direction and the line of sight (LOS) in the comoving frame, f and $(1-f)$ are the fractions of positrons and electrons respectively, Ω_0 is the cyclotron frequency and $g(\beta)$ is a function including products of gamma functions, which depends only slightly on β, i.e. for $\beta = (2.0-2.3)$ we have $g(\beta) \simeq (0.65-0.70)$. Obviously, m_{c0} vanishes for a pure pair plasma with $f = 0.5$. Now, in order to find θ', relativistic aberration has to be taken into account. For a quantitative estimate, consider the case where in the observer frame the LOS and the jet axis form an angle $\theta \simeq 1/\Gamma_b$ with Γ_b the relativistic bulk Lorentz factor of the flow. The common aberration formulae then gives us the angle θ_0' between the jet axis and LOS' measured in the comoving frame. The direction of the intrinsic magnetic

[1] For details, see: www.eso.org/instruments/fors1/pola.html

field seems most likely be perpendicular to the jet axis (e.g., Lister & Smith 2000), thus we may assume $\theta' = \pi/2 - \theta'_0$. For $\Gamma_b \gg 1$, the angle-dependent terms in m_{c0} could be approximated in terms of Γ_b, yielding $m_{c0} = (1-2f)\, g(\beta)\sqrt{6}\,\Gamma_b\,(\Omega_0/\nu')^{1/2}$. While the apparent maintenance of the same sign of handedness of radio CP (e.g., Homan et al. 2001) indeed seems to suggest the presence of a uniform magnetic field component, the rather low degree m_l of LP suggests some form of magnetic field inhomogeneity (e.g. tangled or disordered field component), in which case CP will also be suppressed. If the source region consists of N homogeneous subregions for example, both LP and CP will be suppressed by approximately the same factor $\mathrm{N}^{1/2}$, such that their ratio still remains similar (Jones & O'Dell 1977; Valtaoja 1984). We may thus estimate the required (local) intrinsic magnetic field strength from $(B/1\,\mathrm{Gauss}) \simeq 2\times 10^7 (\nu_{\mathrm{obs}}/10^{15}\,\mathrm{Hz})\, m_{c0}^2\, (0.7/m_l)^2/(\Gamma_b^3\,[1-2\,f]^2\,)$, which yields $B \gtrsim 100$ Gauss for $\Gamma_b = 10$, $m_l = 0.1$, $m_{c0} = 0.01$ and $\nu_{\mathrm{obs}} \simeq \Gamma_b\,\nu' \simeq 10^{15}$ Hz. However, in order to avoid excessive CP violating the radio limits, the coherence length scale of a subregion must be limited such that the number of relevant subregions at a certain frequency for example, is proportional to the square of the synchrotron cooling timescale at that frequency. The degrees of LP and CP in the radio band may then perhaps be attributed to blending of different components in an inhomogeneous jet flow. The derived estimate for the intrinsic magnetic field strength seems quite high (i.e., at least a factor $\sim [50-100]$ times stronger) compared with those values usually found by modelling the multiwavelength spectra in 3C279. However, these values are often based on a single homogeneous sphere model.

2. Propagation-induced CP: The conversion of LP to CP for radiation propagating through a magnetized plasma with elliptically polarized natural wave modes has been widely discussed within recent years as a possible source for producing the observed radio CP of the order of 1% (e.g., Wardle et al. 1998; Ruszkowski & Begelman 2002). The degree of propagation-induced CP peaks around the synchrotron self-absorption turnover frequency with a possible degree of CP up to 10% (Jones & O'Dell 1977). However, at optical frequencies, absorption is negligible and the plasma is usually characterized by the limit of weak intrinsic Faraday rotation (i.e. $\Delta k\, s_l \ll 1$, with s_l the source length). For a plasma with a uniform magnetic field the fractional degree of CP then follows from (cf., Pacholczyk & Swihart 1975; Melrose 1980b)

$$m_c = m_{c0} + \frac{(\Delta k\, s_l)^2}{6}\left[\frac{2\,T\,(T^2-1)}{(T^2+1)^2}\, m_L - \frac{(T^2-1)^2}{(T^2+1)^2}\, m_{c0}\right], \qquad (1)$$

where T denotes the axial ratio of the polarization ellipse (e.g., $|T| = 1$ for circularly polarized natural wave modes) and Δk the wave number difference for the natural wave modes, while m_{c0} is the CP degree of intrinsic synchrotron radiation, see above. For a plasma dominated by non-relativistic particles, we have $|T| \sim 1$ with $(T-1) \propto 1/\nu$ (e.g., Pacholczyk 1973) and $\Delta k \propto 1/\nu^2$, and hence the term in brackets on the rhs of Eq. (1) becomes completely negligible, so that the intrinsic synchrotron contribution is likely to dominate. For a plasma dominated by relativistic particles on the other hand, the natural wave modes are significantly more elliptically polarized (i.e., $T = 1 + \Delta T$ at least over an initial range), however the wave number difference is likely to be much steeper, i.e. $\Delta k \propto 1/\nu^3$ (Kennett & Melrose 1998) and hence the degree of CP again becomes completely negligible. In general, the apparent lack of a positive correlation between m_c and m_l argues against a simple propagation-induced origin of CP in the optical regime (where external depolarization is negligible).

3. Propagation-induced CP in a fully relativistic plasma: Kennett & Melrose (1998) have recently considered the conversion of LP to CP in a highly relativistic plasma. For such a plasma (or in general for a pure pair plasma), the natural wave modes are almost linearly polarized (i.e., $T \gg 1$ at least at sufficient low frequencies), so that for a uniform magnetic field within the source region no detectable CP is produced by propagation effects (cf., Eq. 1). However, if there is a change in the magnetic field direction along the line of sight through the source, CP may still arise (e.g., Hodge 1982; Kennett & Melrose 1998), such that we may have $m_c = m_l \sin\Phi \sin(\Delta k\, s_L)$, where Φ denotes the change in the magnetic field direction and $\Delta k\, s_L = 0.5\,\mathrm{RRM}\,\lambda^3$ with RRM the relativistic rotation measure. For a power law distribution of relativistic particles, one has $\mathrm{RRM} \simeq 3\times10^4\, L\,\langle n_r\,\gamma_{\min}\,B^2\,\sin^2\theta\rangle$ rad/m^3, where $\langle\rangle$ denotes the average over the source length L in parsec, B the magnetic field strength in Gauss and n_r the number density of the relativistic particles in cm^3 (cf., Kennett & Melrose 1998). Assuming equipartition between particles and field, one obtains $\mathrm{RRM} \sim 10^9\,(L/1\,\mathrm{pc})\,(B/1\,\mathrm{Gauss})^4$ rad/m^3. At optical frequencies $\Delta k\, s_L \ll 1$ and hence we may estimate the required magnetic field strength for $L = 10^{16}\,\mathrm{cm} \simeq 3\times10^{-3}$ pc, $m_l \simeq 0.1$, $m_c = 0.01$, $\nu' = 10^{14}$ Hz (e.g., for a Doppler factor ~ 10), implying very high field strengths, i.e. well above 200 G. Again however, the apparent lack of a positive correlation between m_c and m_l argues against a simple realization of such a scenario.

4. Inverse-Compton origin: Optical CP may also arise via inverse-Compton scattering of radio photons by the radio-synchrotron-emitting electrons themselves (Sciama & Rees 1967). As inverse-Compton scattering preserves the polarization properties (e.g., radio CP $\sim 1\%$), the optical continuum could easily be circularly polarized by up to $\sim 1\%$, introducing a link between radio and optical CP. Yet, for such a scenario to be applicable to 3C279, a significant (if not dominant) SSC contribution to the optical continuum has to be assumed, which in view of existing multiwavelength models appears rather unlikely (e.g., Hartman et al. 2001). Spectral information for 3C279 concerning the trend of CP in the radio and optical (preliminary) also seems not readily explainable in an inverse-Compton scenario, but some of these effects are perhaps related to blending effects by other components (cf., Wehrle et al. 2001).

5. Coherent emission mechanisms, operating in the AGN context, have been suggested previously (e.g., Baker et al. 1988; Benford 1992; Lesch & Pohl 1992; Bingham et al. 2003; cf. also Melrose 1991 for a review). The most prominent coherent scenarios are usually based on: (i) Plasma emission, characterized by emission at the local electron plasma frequency $\omega_p \simeq 5.64\times10^4\,[n_e/1\,\mathrm{cm}^{-3}]^{1/2}$ Hz (or the second harmonic) and associated with electrons becoming bunched in space and rather weak magnetic fields ($\omega_p \geq \Omega_0$). Or (ii) electron cyclotron maser emission, i.e. emission near the electron cyclotron frequency $\Omega_0 = e\,B/m_e c \simeq 1.76\times10^7\,[B/1\,\mathrm{Gauss}]$ Hz (or its relativistic variant: $\Omega_0' = \Omega_0/\gamma$, e.g. Bingham et al. 2003) with narrow bandwidth and a high degree of CP. Note, that while models following (ii) may appear promising for the origin of significant radio CP, their predicted narrow spectral bandwidth makes them rather unlikely, given the evidence for radio CP over an extended frequency range. In general, the frequencies ω_p and Ω_0 are much smaller than the frequencies of astrophysical interests, and thus some form of up-scattering is necessarily required in order to explain emission in the radio or optical band in AGN. In the model proposed by Benford (1992) for example, collective broad-band emission resembling a bremsstrahlung spectrum is expected due to relativistic electron beams scattering coherently off concentrations of plasma waves (cavitons). However, the model apparently predicts only very little and negligible CP and is thus not able to account for a significant degree of CP. An interesting variant has also been proposed by Lesch & Pohl (1992): Assuming inverse Compton scattering of Langmuir waves by (monoenergetic) relativistic electrons accelerated in reconnection sheets, their model predicts coherent plasma emission at frequencies $\simeq 2\gamma^2\omega_p/(2\,\pi) \simeq 2\times10^{15}[\gamma/10^4]^2\,[n_e/10^6\mathrm{cm}^{-3}]^{1/2}$ Hz, but offers no analysis of CP properties. Consideration of the global energetics in their model however shows, that coherent emission is (at best) only able to explain the variability but not the steady continuum. It seems thus, that the high degree of CP in the low state is not explainable by such a model.

6. Strong anisotropic particle distributions: A high degree of CP may perhaps also be associated with synchrotron emission from particles with very small pitch angles (i.e., $\gamma \sin\alpha \ll 1$, where α denotes the pitch angle), e.g. due to particles streaming along magnetic field lines (Epstein & Petrosian 1973). Epstein (1973) has shown that in such a case significant CP may occur, although the emissivity is found to be almost completely suppressed for frequencies $\nu > 2\,\gamma\,\nu_0$ and to fall off quite linearly with decreasing frequency below $2\,\gamma\,\nu_0$. However, both the overall spectral energy evolution and the small degree of CP in 3C279 as well as its rapid variability (if associated with the timescale for losses) are not readily explainable via small pitch angle emission in the optical. It could be possible however, that small pitch angle emission is only responsible for the CP contribution, while the overall SED and variability is still dominated by ordinary synchrotron emission. Using $\nu' \sim 10^{14}$ Hz (i.e. $D = 10$), we may then obtain a constraint on the product between the magnetic field and the (intrinsic) electron Lorentz factor for small pitch angle emission given by $\gamma'_{\rm opt}\,(B'/1\,{\rm Gauss}) \gtrsim 2 \cdot 10^7$. For a typical magnetic field strength for the synchrotron emitting region of ~ 1 Gauss, one thus requires $\gamma_{\rm opt} \gtrsim 10^7$ and hence an extraordinary small pitch angle $\alpha \ll 1/10^7$. It seems quite possible, that the onset of plasma instabilities (cf., Jones et al. 1974) and the growth of hydrodynamic waves scattering the particles will prevent the maintenance of such a sharp anisotropy.

7. Special magnetic field configurations: (for propagation effects, cf. also point 3 above). Valtaoja (1984) has argued that the radio CP excess may be related to a special magnetic field topology, e.g. a helical field. For such a magnetic field structure the degree of LP and CP are both dependent on the viewing angle and the helix pitch angle. It could be shown however, that a helical field configuration is less favourable for the production of optical CP via intrinsic synchrotron in the sense that a much higher intrinsic magnetic field strength would be required compared with the uniform field case above (see point 1). Conversion of LP to CP (assuming circularly polarized natural wave modes) in a global helical field on the other hand, requires very high intrinsic rotation measures (RM) well in excess of 10^{10} rad/m^2, which, if realized, would depolarize any radio emission.

8. Accretion disk radiation: Recent modelling of the multiwavelength spectra in 3C279 during several epochs suggests that the UV spectrum of 3C279 may be dominated by accretion disk radiation during times of low γ-ray intensity (Hartman et al. 2001). It may thus be, that the observed optical CP is associated with radiation from the disk rather than from the jet itself. Electron scattering of thermal disk radiation for example, is believed to be responsible (at least in part) for the LP observed from non-blazar AGN (e.g., Agol & Blaes 1996). Yet, simple Thomson scattering, which is wavelength-independent below X-ray energies, may produce LP, but is unable to produce CP. It may be possible however, to introduce optical CP via electron-scattering in a magnetized disk atmosphere or coronae (e.g., Whitney 1991; Gnedin & Silant'ev 1997), where the expected degrees of CP and LP should be of order $m_c \sim \Omega_0/\omega$ and $m_l \sim m_c^2 \sim (\Omega_0/\omega)^2$ for $\omega \gg \Omega_0$, as appropriate for AGN. For any physically realistic magnetic field strength in 3C279 however, the degree of optical CP due to this process seems negligible, even if the observed relation $m_l \gtrsim m_c$ is attributed to blending effects.

9. Scintillation-induced CP in a birefringent screen, which may result in a non-zero variance in Stokes V, has been proposed as a possible cause for the radio CP in AGN (e.g., Macquart & Melrose 2000). Significant scintillation (whether refractive or diffractive) however, is found to require $\Delta x/L > \theta_s$, where Δx is the relative displacement between wave modes with opposite CP, L is the distance from the scattering screen to the observer and θ_s is the angular size of the source. With $\Delta x \sim L\,\lambda^3\,(\nabla_t \mathrm{RM})/2\pi$, this translates into $RM \cdot \lambda^3/(2\pi\,L_t) \gtrsim \theta_s$, where L_t is the characteristic scale length of the transverse RM gradient. A possible, scintillation-induced origin of optical CP thus requires extraordinary high RMs, which would completely depolarize any radio emission from the inner jet of 3C279 and not be consistent with observations suggesting RMs of the order of a few thousand rad/m^2 towards the core (e.g., Taylor 1998).

10. Dust scattering: Polarization may also arise due to dust scattering or transmission through aligned grains either in the host galaxy or our own galaxy. For a scattering optical depth > 1, multiple scattering in an asymmetrical geometry can introduce significant CP provided the sizes of the grains are comparable to the wavelength (e.g., Angel et al. 1976 for NGC 1068). However, in the case of 3C279 a substantial contribution to the circularly polarized flux by dust scattering seems excluded as the observed rapid variations of the polarized flux on timescales of several days are inconsistent with the characteristic spatial dimensions of an (extended) extra-nuclear scattering region. Moreover, the size of the scattering regions is generally expected to smear out any rapid variation.

4 CONCLUSIONS

The foregoing discussion shows that all analyzed scenarios, with the possible exemption of an inverse-Compton origin (which, in turn, appears problematic given the observed spectral information), are unable to account for a degree of optical CP up to $\sim 1\%$ using canonical parameters, suggesting that we may have to add a fundamentally new aspect to traditional emission models. From the above analysis it may be concluded that an intrinsic synchrotron origin in strong, local magnetic fields, an inverse-Compton origin due to scattering of radio photons or an CP origin due to strong anisotropic particle distributions represent the most likely options. Simultaneous radio and optical measurements, and a more detailed theoretical modelling may thus be crucial to further discriminate between these scenarios.

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