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# Is the Long-Term Persistency of Circular Polarisation due to the Constant Helicity of the Magnetic Fields in Rotating Quasar Engines?

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**Abstract.** Many compact radio sources like quasars, blazars, radio galaxies, and micro-quasars emit circular polarisation (CP) with surprising temporal persistent handedness. We propose that the CP is caused by Faraday conversion (FC) of linear polarisation (LP) synchrotron light which propagates along a line-of-sight (LOS) through helical magnetic fields. Jet outflows from radio galaxies should have the required magnetic helicity in the emission region due to the magnetic torque of the accretion disc. Also advection dominated accretion flow (ADAF) should contain magnetic fields with the same helicity. However, a jet region seems to be the more plausible origin of CP. The proposed scenario requires Faraday rotation (FR) to be insignificant in the emission region. The proposed mechanism works in electron-positron ($e^{\pm}$) as well as electron-proton (e/p) plasma. In the latter case, the emission region should consist of individual flux tubes with independent polarities in order to suppress too strong FR – as it was already proposed for FR based CP generation models. The predominant CP is expected to mostly counter-rotate (rotation is measured here in sky-projection) with respect to the central engine in all cases (jet or ADAF, $e^{\pm}$ or e/p plasma) and therefore allows to measure the sense of rotation of quasar engines. The engine of SgrA$^*$ is expected – in this scenario – to rotate clockwise and therefore counter-Galactic, as do the young hot stars in its vicinity, which are thought to feed SgrA$^*$ by their winds. Generally, sources with Stokes-$V < 0$ ($V > 0$) are expected to rotate clockwise (counter-clockwise).

## 1. Introduction

CP emitting compact radio sources like quasars, blazars, radio galaxies, and micro-quasars will be summarised in the following under the general term quasar, assuming that a similar mechanism produces CP in most of them. The level of CP is $\sim 1\%$ and below, usually (but not in the case of SgrA$^*$) much lower than the level of LP. CP is highly time variable on the one hand, but on the other hand it often exhibits a very persistent rotational sense (per source and at nearly all frequencies where detected), which is constant on timescales of decades[1] (10; 9; 3), although exceptions exist. These timescales are far in excess

[1] E.g. SgrA$^*$ and GRS 1915+105. SgrA$^*$ exhibited a stable CP sign on a timescale (20 years) which is 5 orders of magnitude longer than the dynamical timescale of the

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of the dynamical timescale of the central quasar engine from which the emission originates.

Synchrotron radiation from relativistic electrons produces LP, but only a very small and usually negligible amount of CP. A number of mechanisms have been proposed to explain the observed CP, among which FC of LP to CP seems to be the most likely process (5; 1; 13; 11). FC of synchrotron emission is a two-step process, since the emitted polarisation state has to be rotated before it can be Faraday converted into CP. This can happen by FR, as discussed by e.g. Ref. (1) and (13), or it can be done by a systematic geometrical rotation of the magnetic field along the LOS (8; 4).

The motivation for the standpoint adopted here, the assumption that the rotation of LP is a geometric effect rather than FR, is the observational fact that CP changes are very rare, much more rare than LP rotator events, and that a predominant CP sign seems to be persistent in many sources. As explained in the following, this observational fact requires in the FR based models a constant magnetic polarity in the emission region over timescales far in excess of the dynamical timescale of the central engine, since the sign of CP depends on the magnetic field polarity in such models. In the geometrical model discussed here, the CP sign is fully determined by the stable rotational sense of the central engine.

## 2. Magnetic helicity and CP handedness

Before going into the mathematical formalism, we demonstrate how the predominant sign of CP and its relation to the rotational sense of the quasar engine can be understood qualitatively in the proposed scenario. Fig. 1 illustrates the geometry.

Twisted magnetic fields are expected to be a natural ingredient of any quasar central engine due to the rotational nature of the accretion flow. A helically twisted magnetic field is expected to be present in jet outflows, especially if jets are magneto-hydrodynamically launched (2), but also otherwise, due to decreasing rotation speed of the sideways expanding outflow. Further, if the radio emission of a quasar would be produced in an ADAF flows (although this is not the most natural scenario) twisted magnetic fields with the same helicity as in the jet case can be expected. A converging flow onto a black hole spins up due

accretion flow close to the black hole ($\sim$ h). GRS 1915+105 was observed to exhibit a LP-rotator event, but no change in the sign of CP (5). However, counter-examples seem to exist, e.g. a CP sign reversal seems to be observed during the onset of a radiation outburst of GRO J1655-40 in 1994 (11).

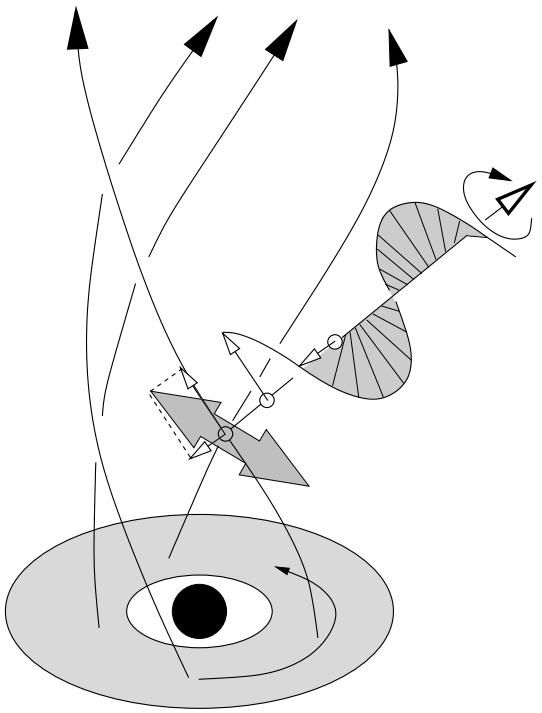

*Figure 1.* Sketch of a possible geometry of a jet source. Shown is a positively rotating accretion disk around a central black hole from which a jet is launched (not shown). Helical field lines of the jet are drawn. The linearly polarised radio emission of energetic electrons within the back side magnetic field lines (the thick arrow indicates the plane of linear polarisation) converts partly into circular polarisation during its journey through the foreground magnetic fields. This conversion is due to the fact that radio emission, with linear polarisation parallel to the magnetic field lines, propagates slower than radio emission, with perpendicular linear polarisation. Our polarised radio emission has perpendicular and parallel components, which oscillate in phase. Caused by the different propagation speeds they get out of phase. The combination of the out of phase oscillating components produces a circular oscillation of the electric field, as sketched.

to angular momentum conservation and should stretch magnetic fields so that they get the same handedness as in the jet case (4).

Linearly polarised synchrotron light has to traverse foreground magnetic fields, which are inclined with respect to the emitting magnetic fields due to the magnetic helicity. The angle between the linearly polarised radio emission and the local magnetic field therefore deviates from 90°. Since this does not correspond to a fundamental electro-

magnetic mode in the plasma, the wave has to be described as a superposition of the fundamental modes.

The two fundamental modes of electromagnetic waves travelling (nearly) perpendicular to a magnetic field in a plasma are the linear polarisation states with electric fields oscillating in a plane which is parallel or perpendicular to the local magnetic field direction. These two modes have different phase velocities since the plasma electrons can respond more freely to an electric field oscillating parallel to the background magnetic field than to an electric field which tries to push the electrons in a direction perpendicular to the magnetic field. Due to the stronger reaction of electrons on parallel LP, their radiative back-reaction onto the propagating wave is stronger compared to the perpendicular LP case. Thereby the parallel LP components is delayed with respect to the perpendicular one. The resulting wave is elliptically polarised, therefore having a CP component.

If the modification of the wave is a small effect, the handedness of the CP is uniquely determined. As can be read off from the figure, but also comes out of a more rigorous calculation, the rotation of the electrical field of the observed wave is retrograde with respect to the rotational sense of the accretion disc (rotation is measured in all cases in the plane of the sky). Numerical experiments indicate that even in the case of strong modification the sign of CP often follows this rule (4).

## 3. Mathematical description

The evolution of the Stokes polarisation parameters $I, Q, U, V$ along a given LOS (here defining the $z$-axis) is governed by

$$\frac{d}{dz}\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} \varepsilon_I \\ \varepsilon_Q \\ 0 \\ \varepsilon_V \end{pmatrix} - \begin{pmatrix} \kappa_I & \kappa_Q & 0 & \kappa_V \\ \kappa_Q & \kappa_I & \kappa_{\mathrm{R}} & 0 \\ 0 & -\kappa_{\mathrm{R}} & \kappa_I & \kappa_{\mathrm{C}} \\ \kappa_V & 0 & -\kappa_{\mathrm{C}} & \kappa_I \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} \qquad (1)$$

(1; 13), where $\varepsilon_{I/Q/U/V}$ is the emissivity and $\kappa_{I/Q/U/V}$ the absorption coefficient of radiation with Stokes parameter $I/Q/U/V$. The emission and absorption coefficients for Stokes-$V$ [2] are much smaller than the ones for Stokes-$Q$ [3]. A special coordinate frame is adopted here, in which the sky-projected magnetic field is parallel to the $y$-axis

[2] CP, clockwise or negatively rotating in sky-projection for $V > 0$, counter-clockwise or positively rotating for $V < 0$.

[3] LP, perpendicular ($Q > 0$) or parallel ($Q < 0$) electric oscillation with respect to the sky-projected magnetic field.

($\vec{B} = (0, B_y, B_z)$), which leads to vanishing synchrotron emission and absorption coefficients for Stokes-$U$ [4]. Note, that in inhomogeneous magnetic fields the local coordinate frame rotates along the LOS in order to keep the $y$-axis aligned with the sky projected field. The effect of this rotation on the Stokes parameter is included in

$$\kappa_{\rm R} = \kappa_{\rm F} + \Omega \text{ by the parameter } \Omega = -2\, d\phi_B/dz\,, \tag{2}$$

which describes the rate of LP rotation along the LOS due to the rotation of the coordinate frame. $\phi_B$ is the position angle of the sky-projected magnetic field in a fixed (non-varying) coordinate frame.[5] The FR coefficient reads

$$\kappa_{\rm F} = -\frac{\tilde{\rho}_{\rm e}\, e^2\, B_z}{\pi\, m_{\rm e}^2\, c^4}\lambda^2, \tag{3}$$

where $\tilde{\rho}_{\rm e}$ gives the effective Faraday-active leptonic charge density. For a non-relativistic plasma $\tilde{\rho}_{\rm e}$ is identical to the leptonic charge density $\rho_{\rm e} = e\,(n_{\rm e+} - n_{\rm e-})$, and for a relativistic plasma $\tilde{\rho}_{\rm e} \propto \rho_{\rm e}$ with a constant of proportionality smaller than one.[6] The sign of FR depends on the sign of $\rho_{\rm e}$ and on the direction of the magnetic field component along the LOS ($B_z$). The FC coefficient

$$\kappa_{\rm C} = -\frac{\tilde{n}_{\rm e}\, e^4\, B_y^2}{4\,\pi^2\, m_{\rm e}^3\, c^6}\lambda^3 \tag{4}$$

is sensitive to the total number of leptonic charge carriers $\tilde{n}_{\rm e} \propto n_{\rm e} = n_{\rm e+} + n_{\rm e-}$ (with a proportionality constant of one in the non-relativistic and smaller than one in the relativistic case) and the square of the perpendicular field strength $B_y^2$. Since both numbers are always positive, $\kappa_{\rm C}$ is always negative (or zero). Since both Faraday coefficients strongly increase with wavelength their importance is largest at lowest frequencies, possibly explaining why CP is often detected close to the synchrotron-self-absorption frequency. In an e/p plasma with diagonal magnetic fields ($|B_y| \sim |B_z|$) the FR coefficient is usually larger in magnitude compared to the FC coefficient, except for extremely high field strength or extremely low frequencies. Both are not expected in our case.

[4] LP, $\pi/4$ inclined to the sky-projected magnetic fields.

[5] For a purely stochastic magnetic field, $\Omega$ is a random variable with zero mean. However, if there is a systematic twist in the magnetic fields along the LOS $\Omega$ has a preferred sign. The sign of $\Omega$ does not depend on the polarity of the field, only on the handedness of the twist along the LOS.

[6] $n_{\rm e\pm}$ is the $\rm e^{\pm}$ number density respectively. In the relativistic case an identical spectral distribution of the two species is assumed, otherwise they enter $\tilde{\rho}_{\rm e}$ with different proportionality factors.

Since there is no direct conversion of $Q$ synchrotron emission to $V$ (the corresponding matrix element in Eq. 1 is zero) CP has to be produced via a two-step conversion in this setting: After rotation (due to twist or FR) of $Q$ into $U$ it is further converted by FC to $V$.

In a relatively homogeneous source the sign of $V$ depends only on the sign of $\kappa_{\rm R}$ and therefore on the polarity of the magnetic field with respect to the LOS in the case that FR dominates, or on the magnetic helicity, if FR is sufficiently suppressed. The total rotational depth ($\tau_{\rm R} = \int dz\, \kappa_{\rm R}$) should be sufficiently high on the one hand, but on the other hand it should be not too large within the converting region, otherwise the continued rotation changes the sign of $U$, which leads to the production of $V$ with the opposite sign and therefore cancelling of CP. To have this condition met for FR in the right frequency range requires some level of fine-tuning. In the case that $\kappa_{\rm R}$ is dominated by the helical contribution, typical expected geometries give $\kappa_{\rm R} \sim 1$, which is ideal for CP production: An effective CP production can be achieved if both $\tau_{\rm R}$ and $\tau_{\rm C} = \int dz\, \kappa_{\rm C}$ are simultaneously of the order one, since $V \approx \frac{1}{6}\, \tau_{\rm F}\, \tau_{\rm C}\, Q$ for $\tau_{\rm F} \ll 1$ and $\tau_{\rm C} \ll 1$ within an optically thin region[7], and much less than this if $\tau_{\rm F} \geq 1$ and/or $\tau_{\rm C} \geq 1$ due to over-rotation and/or over-conversion.

**FR based CP generation:** Ref. (1) and (13) demonstrated that a significant CP production can be achieved even in the case of a very large microscopic FR coefficient if the magnetic field is mostly stochastic. The contributions of $\kappa_{\rm F}$ with differing signs due to magnetic field reversals can cancel each other, leaving only a small total Faraday depth $\tau_{\rm F}$ due to an assumed weak mean field. The strength and sign of this mean field determines the strength and sign of the resulting CP respectively. Although some fine-tuning is also necessary in this scenario in order to simultaneously have the right order of FR and FC, the larger number of free parameters (field strength and coherence length, ratio of mean to stochastic field components, $\tilde{\rho}_{\rm e}$, $\tilde{n}_{\rm e}$) provides a sufficiently large parameter space to make this scenario a plausible explanation for the observed CP for a wide range of objects. Ref. (13) showed that this approach can produce CP in the case of an e/p and also in the case of a (charge-asymmetric) $e^{\pm}$ plasma.

However, in order to explain the long-term stability of the observed sign of $V$ it has to be assumed in their model that the weak magnetic mean flux has to retain its polarity. This might surprise, since the dynamical time scales in several of the observed systems are orders of magnitudes smaller than the time-scale over which stability of the sign

[7] For an optically thick source, using only the region up to $\tau = 1$ is a coarse approximation, leading to $V \approx \frac{1}{6}\, \tau_{\rm F}\, \tau_{\rm C}\, Q/\tau^2$.

of $V$ could be established. Furthermore, the large fluctuations in $V$ indicate strong temporal variations in the strength of the mean field. Since the latter should be dynamically unimportant, its stable polarity may be best explained if it results from an environmental large scale field, which gets dragged into the central engine.

**Magnetic helicity based CP generation** requires FR rotation to be sufficiently suppressed. This could be due to a vanishing leptonic charge density ($\rho_{\rm e}$) as expected for a $e^{\pm}$ plasma, or due to the presence of aligned, separate or nested flux tubes (with a global large scale twist) with independently oriented (but aligned) internal magnetic fields. As Ref. (1) and (13) showed for the stochastic field case, this can strongly reduce the Faraday depth also in the case of a large microscopic $\kappa_{\rm F}$. In their cases, some fine-tuning was required since FR should be somehow suppressed, but not completely, leaving to sufficient FR from $Q$ to $U$. This fine-tuning is not required here, since the geometrical rotation provides $Q$ to $U$ rotation even in the case of fully suppressed FR. $\kappa_{\rm C}$ is not affected by LOS reversals of the magnetic field direction, since it only depends on the invariant $B_y^2$.

A typical geometry is sketched in Fig. 1 for an approaching jet, which is rotating positively (in sky-projection). The rotation sense of the sky-projected magnetic fields seen by a photon flying from its emission point (where the synchrotron process provided it with $Q > 0$) to the observer is therefore also positive, leading to $\Omega = -2d\phi_B/dz < 0$ in this geometry. Thus, in our limit $\kappa_{\rm F} \ll \Omega$ we obtain $V \propto \Omega\,\kappa_{\rm C}\,Q \geq 0$ since $\kappa_{\rm C} \leq 0$ always. In this picture a positively rotating approaching jet emits negatively (clockwise) rotating circularly polarised light. Since the counter jets should exhibit an oppositely twisted magnetic field, it should produce CP of the opposite sign. However, the approaching jet dominates the total emission due to relativistic beaming so that its CP emission dominates the CP of both jets. We can conclude that the rotation of the received photons of a synchrotron emitting jet source are expected to be retrograde to – and therefore reveal – the sense of rotation of the central engine, which is the rotation of the accretion disk and/or the black hole.

## 4. Discussion and outlook

A helical magnetic field can produce circularly polarised synchrotron emission due to FC. If FR is sufficiently suppressed the sense of CP rotation is expected to be opposite to the one of the central engine. The required FR suppression can be due to a charge symmetric $e^{\pm}$ plasma, in which FR is absent, or due to small-scale magnetic field

polarity changes which produce cancelling FR contributions, but do not affect FC if the different flux tubes show alignment. The proposed model as the following properties:

1. The sign of the CP does not depend on the presence of a mean field, but on geometrical properties of the flow pattern in the central engine of a quasar, which are fixed by the system's angular momentum. This may explain naturally the observed sign persistence of the CP over periods which exceed the dynamical timescales of the system by orders of magnitude.

2. The requirement that the rotation of the angle between LP and projected magnetic field is of the order one (not much higher, since over-rotation reduces CP, not much lower in order to have FC operating) within the optically thin part of the emission region, is naturally fulfilled by the geometrical properties of jet and ADAF flows.

3. CP is still converted LP in this scenario, so that the variability of CP should exceed the one of LP as observed.

4. The mechanism can work in jets and in ADAFs. It is able to produce CP in an $e^{\pm}$ and in an e/p plasma.

5. The relatively large robustness of the mechanism to variations in the underlying source properties may explain why CP appears in a large variety of very different systems, such as micro-quasars, low luminosity AGNs, and powerful quasars.

There are conditions, under which the here proposed relation between the (predominant) rotational sense of CP and the rotation of the central engine is not valid anymore.[8] However, the rarity of CP sign reversals

[8] Whenever the average FR is stronger than the twist in the magnetic fields along the LOS, the sign of the average magnetic field will determine the sign of CP as in the models of Ref. (1) and (13). This may occur temporarily, if thermal plasma gets mixed into an $e^{\pm}$ jet. If the emission region contains an e/p plasma, the occurrence of a mean magnetic field – either as a statistical fluctuation, or due to some physical reason – can increase the average Faraday depth and lead to a CP reversal. External CP generation from LP due to environmental scintillation also can mask the intrinsic CP signature of a quasar. Also within the scenario in which CP is due to bending in magnetic fields, CP sign reversals are possible, whenever the magnetic twist within the emission region is not linked to the central engine rotation. This may happen temporarily in violent shocks in a jet outflow, and would suggest that CP sign reversals of this origin are likely accompanying emission outbursts of the source. This may explain the observed CP sign reversal in GRO J1655-40 during an outburst in 1994, as reported by (11).

indicate that such conditions should be exceptional, if CP is due to the here proposed mechanism.[9]

The proposed mechanism provides testable predictions:

1. The sign of CP from a quasar measures the rotation direction of the quasar's engine. The electric vector of radio emission should rotate retrograde in the sky-plane with respect to the engine rotation. Positive $V$ polarisations implies therefore positive = counter-clockwise rotation (on the sky) of the engine.

2. Thus, we expect SgrA*, which exhibited $V < 0$ during the last 20 years, to rotate clockwise. This is retrograde with respect to the galactic rotation and the rotation of the molecular gas cloud in the galactic centre. However, it has the same rotation sense as the population of young hot HeI stars in its direct vicinity (7), which were proposed to feed SgrA* via their stellar winds (6). Conservation of angular momentum in this wind should lead to a retrograde (clockwise) rotating accretion disk.

3. We expect the microquasars GRS 1915+105 and SS 433 (both exhibit $V < 0$) also to rotate clockwise, and we could give corresponding expectations for the other sources with detected CP.

4. The predominant sign of CP should be temporally constant. If the model is correct, quasar-like CP sources should only exhibit CP flips under exceptional circumstances.

5. CP from the counter jet should have opposite handedness than CP from the approaching jet. This prediction may allow a discrimination of the presented model from FR based scenarios, since in the latter the same predominant CP sign is expected from both jets for a dipole-like mean field component.

If the scenario of CP production proposed here could be demonstrated to be operatively in quasars, it would give us a tool to measure the sense of rotation of the most powerful and enigmatic engines of the

[9] A CP sign flip of SS 433 is repored in these proceedings (12). It is possible, that this is caused by a magnetic field reversal, since the jets of SS 433 are known to contain ions, so that Faraday rotation might be the dominant CP generation mechanism. However, it is also possible that the helical twist is generating the CP, and the CP flip is caused geometrically: the precession of the jet can lead to a geometry within the co-moving jet material, in which the photon path towards the observer is oppositely directed with respect to the jet flow (12). If this is the case, both models, the Faraday rotation based and the magnetic twist based, would have a CP sign flip. Further, if this is the case, two CP reversal are expected within each precession period, so that this scenario has a clear observational signature.

universe – the violent matter flows in the direct vicinity of black holes – by simply looking at the spin of the received photons.

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