The nature of jets: evidence from circular polarization observations

John F. C. Wardle and Daniel C. Homan

*Physics Department, Brandeis University, Waltham, MA 02454, U.S.A.*

**Abstract.** We review recent observations of circularly polarized radiation from AGN made with the VLBA and with the ATCA. We also discuss briefly the detections of the Galactic sources Sag A* and SS433. The origin of the circular polarization is still an open question in most cases, and we discuss four possible mechanisms. Detectable circular polarization is a common property of quasars, but not of radio galaxies, and is always associated with the compact core. There is growing evidence that the sign of the circular polarization stays the same over at least two or three decades in time, suggesting it is a fundamental property of the jet.

1. **Introduction**

Circular polarization (CP) measurements of extragalactic radio sources have long enjoyed the dubious reputation of being challenging to carry out and hard to interpret. After a period of activity in the 1970’s and early 80’s (summarized by Weiler & de Pater 1983) there have been few new observations until recently.

The renewed interest stems from two developments. First, the Australia Telescope Compact array (ATCA) can now measure CP with a limiting accuracy as low as 0.01% (Rayner, Norris & Sault 2000). This remarkable precision is because the array was specifically designed to measure CP, and uses orthogonal linearly polarized feeds at each antenna. Second, the excellent performance of the VLBA has permitted the detection of CP in more than 20 AGN (Wardle et al. 1998, Homan & Wardle 1999, Homan, Attridge & Wardle in preparation). Because the VLBA is equipped with circularly polarized feeds, the limiting accuracy is ~ 0.1%, some ten times worse than ATCA. In compensation, the VLBA has about one thousand times higher resolution. Most measurements have been of AGN, but we note that CP has also been detected in the Galactic sources Sag A* using the VLA (Bower, Falke & Backer 1999) and SS433 using ATCA (Fender et al. 2000).

The promise of CP measurements is that they may permit, depending on the emission mechanism, direct measurement of the magnetic field strength and its polarity, the true magnetic flux carried by a jet (and hence generated at the central engine), the low energy cut-off in the relativistic electron spectrum, and the composition of the radiating plasma - whether it is predominantly an electron-proton plasma or an electron-positron plasma, or a mixture of the two. None of these can be determined directly from measurements of the first three
Stokes parameters (total intensity, $I$, and linear polarization, $Q$ and $U$). The fourth Stokes parameter, $V$, corresponding to the circularly polarized component of the radiation field, therefore offers a new way of measuring fundamental physical properties of AGN, and also the smaller scale jets in Galactic X-ray binaries.

2. Circular polarization observations of AGN

Following the VLBA detection of CP in the quasar 3C 279 at 15 GHz (in which we argued that the jets were predominantly an electron-positron plasma, Wardle et al. 1998), we published extensive 15 GHz observations of CP in four AGN (3C 84, PKS 0538+134, 3C 273, 3C 279; Homan & Wardle 1999). This was part of a monitoring program in which sources were observed every two months for a year. In each source that was detected (4 out of $\approx 32\%$, at fractional polarization levels, $m_C$, from 0.3 to 1.0%), the CP signal was somewhat variable but present throughout the year (and with the same sign), setting a minimum time scale for large changes of CP in AGN. The CP signal was always associated with the VLBI core, but often not coincident with it (e.g. 3C 279). Another clear example is 3C 273 (see Figure 1), where the CP signal first appeared in the core concurrent with the appearance of significant linear polarization. It then moved away from the core and down the jet, coincident with a new moving component in total intensity (Homan & Wardle 1999). This behavior shows that the CP is intrinsic to the source (as opposed to a foreground effect or a calibration error). It is most prominent where the optical depth is of order unity (as expected on theoretical grounds, Jones & O’Dell 1977, Jones 1988), and at least in these two quasars is associated with new components or shocks emerging from the optically thick base of the jet.

A VLBA survey of 40 blazars at 5 GHz (Attridge et al. 1998) has been reanalyzed for circular polarization (Homan, Attridge & Wardle, in preparation). We detected CP in 13 sources ($\approx 33\%$), with $m_C$ between 0.14 and 0.46%, somewhat lower than those measured at 15 GHz. This sample is large enough to look for obvious correlations. We detected CP in 11 out of 29 quasars, but only 2 out of 10 BL Lac objects. This is not yet statistically significant. The only galaxy in the sample, OQ 208, was not detected. More interesting, there was no correlation between the detectability of CP and the fractional linear polarization of the core component.

In a small survey using the VLBA at 8 and 15 GHz, we have detected CP in 3 sources out of 11 ($\approx 27\%$) at 8 GHz. An image of PKS 1127-114 at 8 GHz is shown in Figure 2. The 15 GHz data are currently being reduced to obtain the CP spectrum.

A more sensitive ATCA survey of of 32 AGN at 5 GHz (Rayner et al. 2000) yielded 17 detections ($\approx 52\%$) with (integrated) fractional polarization levels $m_C$ from 0.03 to 0.45%. If the 8 galaxies are excluded, only one of which was detected, the detection rate rises to 65%. (This result may be relevant to unified schemes, e.g. Barthel 1989). Rayner et al. also found no difference in the detection rates for quasars and BL Lac objects, and no dependence on the fractional linear polarization of the source. The most strongly circularly polarized source was the the intra-day variable (IDV) source PKS 1519-273 that
Figure 1. 3C 273 at 15 GHz, epoch 1996.74, showing circular polarization (grey scale) and total intensity (factors of 2 contours). The peak CP flux is $V = -37$ mJy, $V/I = -0.5\%$, located on a new component ($I = 7.8$ Jy) emerging from the core region.

Figure 2. PKS 1127-114 at 8 GHz, epoch 1998.01, showing circular polarization (grey scale) and total intensity (factors of 2 contours). The peak CP flux is $V = -3.2$ mJy, $V/I = -0.3\%$, coincident with the core ($I = 1.2$ Jy).
varied between $-0.25$ and $-0.45\%$ on a time scale of \textit{hours} (Macquart et al. 2000).

Thus it is clear that detectable circular polarization is a common phenomenon among flat spectrum radio sources, and is associated with the most compact features. It is interesting to compare recent measurements to those made two to three decades ago (Weiler & de Pater 1983, Komesaroff et al. 1984). This can be done for 29 sources if we ignore mismatches in observing wavelength (the older measurements tended to be at longer wavelengths). We find that all sources that exhibited strong CP ($>0.15\%$) in the past have been detected recently at comparable levels, and all sources that were weak or not detected in the past are presently also weakly polarized or not detected. Thus despite its variability, the overall level of CP appears to be a persistent property of these sources. As yet we do not understand why some sources consistently exhibit strong CP while others do not.

3. Mechanisms for producing circular polarization

The origin of the observed circular polarization signal is far from settled. One clue comes from its spectrum. It is well known that the intrinsic circular polarization of optically thin synchrotron radiation has a spectrum $m_C \propto \nu^{-0.5}$, where $m_C = V/I$ is the fractional CP. For 3C 279 we argued in favor of Faraday conversion, based in part on the observed steep spectrum (Wardle et al. 1998). However, in other AGN the spectrum of the integrated fractional CP is rather flat (Rayner 2000), while in SS433, Fender et al. (2000) found $m_C \propto \nu^{-0.9}$. It is important to note that for a Blandford-Königl (1979) inhomogeneous jet, the CP spectrum may be quite different than for a homogeneous component (see section 4). Coherent emission mechanisms, that may be relevant to AGN cores, and especially to intra-day variable (IDV) sources can generate copious CP, and a particularly interesting new mechanism, scintillation by a birefringent screen, has been proposed by Macquart & Melrose (2000). We now briefly review these mechanisms.

3.1. Coherent radiation mechanisms

These have been most recently discussed by Benford & Tzach (2000) and by Bingham et al. (these proceedings). Coherence may arise from particle bunching, or from an anisotropic distribution function leading to a negative absorption coefficient and maser action.

Both cases appear to produce rather high fractional CP (though this may be diluted in a real source) and are intrinsically narrow band phenomena. The latter property can be tested. It appears to be ruled out by the rather flat CP spectrum observed in most AGN over widely separated wavelengths. Even for the IDV source PKS 1519-273, the fluctuations in both $I$ and $V$ were strongly correlated between 4.8 and 8.6 GHz (Macquart et al., these proceedings). Also, over a much narrower frequency range, we find that for sources observed at the VLBA, the CP signal is equally present in all 4 IF bands.
3.2. Scintillation

A new and intriguing possibility proposed by Macquart & Melrose (2000) is that of scintillation by a birefringent screen, which can generate circular polarization from the total intensity (Stokes I). In this mechanism, Faraday rotation in the screen causes a very small displacement of the left- and right-hand components of the total intensity. The two amplitude patterns produced by scintillation are therefore also slightly displaced from each other. As they sweep over the antenna there is an instantaneous, fluctuating CP signal, though the time averaged CP must of course be zero.

Macquart & Melrose show that the rms fractional CP can be written as

\[ m_C \simeq \frac{\Delta x}{r_{\text{scint}}} m_I, \]

where \( m_I \) is the fluctuation index in total intensity, \( r_{\text{scint}} \) is the linear scale of the scintillation pattern (whether diffractive or refractive) in the observer plane, and \( \Delta x \) is the relative displacement of the right and left circularly polarized scintillation patterns in the observer plane.

They demonstrate that birefringent scintillation in our own Galaxy produces an insignificant effect for AGN, but may well contribute to the observed CP in pulsars. For AGN (and for Sag A*) they suggest a screen close to the source. The displacement of the two scintillation patterns at the observer is

\[ \Delta x \simeq \frac{L\lambda^3}{2\pi} \nabla_r RM, \]

where \( L \) is the distance from the screen to the observer, and \( \nabla_r RM \) is the transverse gradient in Rotation Measure at the screen. For significant scintillation, they also require that \( \Delta x/L > \theta_s \), where \( \theta_s \) is the angular size of the source. These lead to rather stringent requirements on the screen, and also suggest that it should be mainly a long wavelength phenomenon. Macquart and Melrose apply this mechanism to the quasar 3C 345, and find they require a RM gradient of about \( 10^6 \) rad m\(^{-2}\) pc\(^{-1}\). So far, typical RM gradients measured in quasar cores are of the order of a few hundred rad m\(^{-2}\) pc\(^{-1}\) (Taylor 1998), though in the innermost 0.1 pc or less, it could certainly be much higher. A second problem is that such a RM gradient would almost certainly completely depolarise a typical VLBI core or inner component. This might not be a problem for an IDV source such as PKS 1519-273, where the inferred source size is extremely small, or for Sag A*, which exhibits no detectable linear polarization at any wavelength.

The timescales they derive for scintillation induced CP are very short: a few minutes for diffractive scintillation, and several hours for refractive scintillation. The sign of the induced CP should reverse on these timescales. These are much too short for the observations of most AGN, but again are not a problem for IDVs or Sag A*. It is also possible that a different source-screen geometry might lead to much longer timescales.

3.3. Intrinsic circular polarization

Synchrotron radiation has a small intrinsic component of circular polarization (Legg & Westfold 1968). In a uniform magnetic field, the maximum fractional
circular polarization at frequency $\nu$ is $|m_C| \approx 1/\gamma$, where $\gamma$ is the Lorentz factor of electrons radiating at $\nu$. More realistically, for a combination of a uniform and a tangled field, we can write

$$m_C = -1.6 \Lambda (\nu/\nu_{\perp})^{-\frac{1}{2}} (B_u/B_{\perp}) \sin \epsilon,$$

where $B_u$ is the uniform component of the magnetic field (assumed here to be parallel to the jet), $B_{\perp}$ is the r.m.s. value of the magnetic field in the plane of the sky, $\nu_{\perp} = eB_{\perp}/2\pi mc$ is the electron gyro frequency, and $\epsilon$ is the angle between the jet normal and the line of sight in the frame of the emitting fluid $(\cos \epsilon = \delta \sin \theta)$. The factor $\Lambda$ accounts for the reduction in circular polarization if $B_z$ is not also unidirectional (i.e. if there are reversals in direction of $B_u$), and if the charges of the radiating particles are not all the same sign. Defining $f_B = \int |B_u| dl / \int |B_{\perp}| dl$, and $f_C = (n^- - n^+)/ (n^- + n^+)$, where $n^-$ and $n^+$ are the electron and positron densities respectively, then $\Lambda = f_B f_C$. The Faraday depth is also reduced by the same factor.

In a real jet, even if the component of magnetic field parallel to the jet is unidirectional at its base ($f_B \sim 1$), it will decay faster with radius ($\propto r^{-2}$) than the transverse field components ($\propto r^{-1}$). Further down the jet, the parallel component of field is likely to be dominated by sheared loops of field (e.g. Begelman, Blandford & Rees 1984) and $f_B$ (and hence $\Lambda$) is likely to be small, regardless of whether the jet is composed of electrons and positrons or electrons and protons.

This factor has generally been neglected in the literature, and it should not be. It applies both to the interpretation of circular polarization, and to the interpretation of Faraday rotation. It is sometimes assumed that the value of $(B_u/B_{\perp})$ is indicated by the degree of linear polarization, but this may be quite misleading. For instance, in a Laing sheet topolgy (Laing 1980), the fractional linear polarization may approach 70%, but internal Faraday rotation and the intrinsic component of circular polarization will both be zero.

### 3.4. Faraday conversion

A less well known but equally important mechanism for generating circular polarization is Faraday conversion (Jones & O’Dell 1977; Jones 1988). This is based on the fact that the normal modes for radiative transfer in an anisotropic plasma are not purely circular (which leads to Faraday rotation), but slightly elliptical. The small component of linear birefringence converts Stokes parameter $U$ to $V$, and vice versa. Both rotation and conversion are caused by the lowest energy relativistic electrons, and therefore serve as a probe of the low energy end of the electron energy distribution, which is otherwise unobservable. An important difference between them is that Faraday rotation is proportional to the electron gyro frequency, $\nu_{\perp} = eB_{\perp}/2\pi mc$, and hence to the sign of the charge on the electrons, while Faraday conversion is proportional to $\nu_{\perp}^2 \propto e^2 B^2$. Thus an equal mixture of electrons and positrons ($f_C = 0$) can produce Faraday conversion, but not rotation, as can sheared loops of magnetic field ($f_B = 0$).

It is also important to note that Faraday conversion acts on Stokes $U$, while the synchrotron mechanism produces only Stokes $Q$ (in the local frame of the magnetic field). Stokes $U$ can be produced stochastically by a tangled field, or, more efficiently, by internal Faraday rotation. At small optical and
Faraday depths, the fractional circular polarization produced by conversion is
\[ m_C \approx \frac{1}{6} \tau_F \tau_C m_L^2, \]
where \( \tau_F \) and \( \tau_C \) are the Faraday depth and “conversion
depth” respectively, and \( m_L \) is the fractional linear polarization. For a power
law distribution of electron Lorentz factors, \( n(\gamma) \propto \gamma^{-2} \) (corresponding to \( \alpha = 0.5 \)), with a low energy
cutoff at \( \gamma = \gamma_{\text{min}} \), \( \tau_F \) and \( \tau_C \) can be written as (Jones &
O’Dell 1977)
\[
\tau_F \approx 1.27 \tau \Lambda \left( \frac{\gamma}{\gamma_{\text{min}}} \right)^2 \frac{\ln \gamma_{\text{min}}}{\gamma_{\text{min}}} \frac{B_u}{B_L} \sin \epsilon
\]
\[ \tau_C = -0.96 \tau \ln(\gamma/\gamma_{\text{min}}) \]
where \( \gamma \) is the Lorentz factor of the radiating electrons. These expressions apply
to the optically thin, Faraday thin case. The strong wavelength dependence of
both \( \tau_F \) and \( \tau_C \) imply a very steep CP spectrum, \( m_C \propto \nu^{-5} \). As the Faraday
depth increases, the effect saturates, and \( m_C \propto \nu^{-1} \). At appreciable optical
depth, the spectrum flattens further. The reader should refer to Jones & O’Dell
(1977) for the complete expressions for a homogeneous source. Also, at significant
Faraday and conversion depth there can be nulls and sign reversals in the CP
(since \( Q \) has been converted to \( -U \) etc.) along a single line of sight, or in a
uniform slab (Kennett & Melrose 1998). In a real source, where we average over
many lines of sight, the effect is more likely to lead to depolarization of both the
circularly and linearly polarized radiation.

Certain magnetic field topologies may also produce efficient conversion,
without the need for internal Faraday rotation (e.g. Hodge 1982). For instance,
in a helical magnetic field, ‘Stokes Q’ from the back of the jet may appear as
‘Stokes U’ to the front of the jet, depending on the pitch angle. The sign of
the CP is determined by whether the helix is left handed or right handed. A
force-free magnetic field is another such configuration, though we have not yet
calculated the resulting CP in these cases. Since internal Faraday rotation is
not invoked here, the CP spectrum will be much less steep, and the problem of
sign reversals much less severe.

Finally, the expression for \( m_C \) at the beginning of this section contains two
factors of \( m_L \), the fractional linear polarization. One factor is because conversion
acts on the linearly polarized radiation, and the second factor expresses the
conversion efficiency in a partially ordered field. One might therefore expect a
strong correlation between \( m_C \) and \( m_L \), but this is not generally seen in either
the ATCA or the VLBA results (though in 3C 273, CP did not appear until
significant linear polarization also appeared in the core). A plausible reason for
the lack of an obvious correlation is that the CP originates from the core regions,
which are thought to be depolarized by an external Faraday screen (Cawthorne
et al 1993, Taylor 1998, Wardle 1998) in the nucleus of the source.

4. The circular polarization spectrum, and inhomogeneous jets

In general a steep CP spectrum favors Faraday conversion (Jones & O’Dell 1977),
where it can vary in the range \( \nu^{-1} \) to \( \nu^{-5} \) in an optically thin homogeneous
component, while the intrinsic component has a \( \nu^{-1/2} \) spectrum. Both are
flattened by appreciable opacity.
But a flat spectrum can also result for the “core” of a Blandford-Königl (1979) inhomogeneous jet, where the optical surface moves down the jet with increasing wavelength, and this region is seen as the ‘core.’ In their canonical case ($B \propto r^{-1}$, electron density $\propto r^{-2}$, and $\alpha = 0.5$), the location of the optical surface $r_{\tau=1} \propto \nu_{\text{obs}}^{-1}$. The Lorentz factor of the electrons radiating at $\nu_{\text{obs}}$ from that region is $\gamma \sim \nu_{\text{obs}}/\nu_{B,1}$, which is independent of $\nu_{\text{obs}}$. Since the intrinsic component of CP is $\sim 1/\gamma$, it too is independent of $\nu_{\text{obs}}$, and the CP spectrum is flat.

Similar considerations show that Faraday conversion is also independent of $\nu_{\text{obs}}$ (the Blandford-Königl model is isothermal, so $\gamma_{\text{min}}$ is also constant). It follows that there will also be no sign reversals at longer wavelengths.

The point is that the simple spectral signatures in homogeneous sources almost certainly will not be seen in real jets, where opacity and inhomogeneity cannot be ignored. Unfortunately, this probably requires numerical simulations using the full equations of polarized transfer to calculate the expected CP.

5. Electron Positron Jets?

If the dominant production mechanism for CP in AGN is Faraday conversion, then this requires that the electron energy spectrum extend down to low energies in order to get sufficient mode conversion from linear to circular polarization. The most robust result for 3C 279 (Wardle et al. 1998) was that over a wide range of source models, the low energy cut-off in the electron energy spectrum had to be below $\gamma_{\text{min}} = 20$, and could be much lower. We then suggested that the radiating particles were predominantly an electron-positron pair plasma so that the jet did not carry far more kinetic energy than is observed to be dissipated.

This argument has also been made by others, e.g. Reynolds et al. (1996) for M87 and Hirotani et al. (1999, 2000) for 3C 279 and 3C 345; and see Celotti & Fabian (1993) for a different conclusion. The argument assumes that we can correctly estimate the kinetic energy carried by a jet, which is not altogether clear (c.f. various contributions in these proceedings). However, the argument is greatly strengthened if the presence of low energy particles can be inferred directly from CP measurements.

It should be noted that if $\gamma_{\text{min}}$ is small enough, then the same low energy particles that cause Faraday conversion will also give excessive Faraday rotation and depolarization unless $\Lambda = f_B f_C$ is also small. The degeneracy between $f_B$ and $f_C$ is not easily broken, but if $f_B$ can be estimated in some other way, then CP observations could demonstrate the presence of electron-positron pairs (i.e. $f_C < 1$), independent of the energy argument.

Clearly we would like to apply the same analysis to other sources in which we have detected CP, to see if electron-positron pairs are a general characteristic of extragalactic jets. To do so requires multi-wavelength observations to establish the CP spectrum, and to determine the magnetic field strength from the self-absorption turnover. Such observations are in progress.
6. SS433 and Galactic jets

The discovery of circular polarization in the celebrated x-ray binary SS433 (Fender et al 2000) opens the possibility of making high resolution CP observations of this and other Galactic jets, where the similarities and differences compared to AGN jets are equally striking. The ATCA observations found a strong CP signal \( m_C \approx 0.6\% \) at 1.5 GHz with a spectral index of \(-0.9\). The CP flux density was several mJy, easily detectable with the VLBA, and presumably the local fractional polarization is considerably higher. The CP mechanism is unclear (and its spectrum is complicated by both synchrotron opacity and free-free absorption), but both Faraday conversion and the intrinsic mechanism are possible. The latter is a candidate because the magnetic field is stronger than is typical in AGN – Paragi et al. (1999) estimate 0.4 G at the position of the 1.5 GHz core – and the magnetic field structure may be simpler, with fewer field reversals. If the former applies, then it may be possible to determine whether the composition of the radio jets is primarily pairs or baryonic.

SS433 precesses with a period of 164 days, and the geometry is well understood (Margon & Anderson 1989). This should produce a clear signature in the circular polarization in both the intrinsic and the conversion mechanisms. For most of a period, the sign of CP should be the same in both the jet and the counter jet. But when the jet makes an angle of less than 75° to the line of sight, its sign should reverse. This is a straightforward consequence of relativistic aberration \( v_{jet} = 0.26c \); for part of each period we are, in effect, looking up the jet instead of down it. Because of the changing geometry, we have a unique opportunity for detailed analysis of the polarization properties of these jets. This may shed light on the physics of extragalactic jets, for which we do not have the luxury of observing from different angles.

7. Long-term persistence of the sign of CP

It was pointed out in section 2 that the presence or absence of detectable CP appears to be a persistent property of AGN over two to three decades. Equally interesting, for the ten strongly polarized sources for which we have both recent and historical data, eight show the same sign of circular polarization at both epochs. Komesaroff et al (1984) pointed out that the sign of the CP tended to persist over the few years of their observations. Now it appears that the sign persists over decades (pointed out for a smaller sample by Homan & Wardle, 1999). This is highly significant because it is very much longer than the characteristic time scale of the CP variability and of outbursts in total intensity (typically a year or so). This suggests that the sign is determined by a fundamental and long-lived property of the jets. In both the Faraday conversion and the intrinsic synchrotron mechanisms for generating the observed CP, the sign is determined by the net unidirectional component of the magnetic field, i.e. by the net magnetic flux carried by the jet. It has long been realized that most of the magnetic field consists of sheared and stretched loops (Begelman, Blandford & Rees 1984), and that the true net flux \( \int \mathbf{B} \cdot dA \) must be much smaller than the value of \( B_{rms} \times A \) (A is the area of the jet cross-section) often calculated for synchrotron emitting jets.
CP measurements may permit proper calculation of the net magnetic flux in jets, which, assuming flux conservation, gives the magnetic flux at the central engine. This is a fundamental parameter in electro-magnetic models of jet production (e.g. Blandford & Payne 1982; Lovelace & Romanova 1995; Meier, these proceedings; Begelman, these proceedings), and may also relate properties of the jet to those of the central massive black hole (Rees, 1984).

8. Conclusions

It was stated in the introduction that “circular polarization (CP) measurements of extragalactic radio sources have long enjoyed the dubious reputation of being challenging to carry out and hard to interpret.” This is still true. It is hoped that this review will convince some readers that the unique information contained in such observations makes them, nevertheless, extremely valuable and worthwhile.

Acknowledgments. This work was supported by grants from the NSF and NASA.

References

Attridge, J. M., Roberts, D. H., & Wardle, J. F. C. 1998, 'VLBA Imaging of a Large Sample of Blazars,' in Radio Emission from Galactic and Extragalactic Compact Sources, IAU Colloquium 164, ASP Conference Series Vol 144, Eds: J. A. Zensus et al. (ASP: San Francisco), 159-161
Barthel, P. D. 1989, 'Is every quasar beamed?,' ApJ, 336, 606-611
Begelman, M. C., Blandford, R. D. & Rees, M. J. 1984, 'Theory of extragalactic radio sources,' Rev. Mod. Phys., 56, 255-351
Benford, G. & Tzach, D. 2000, 'Coherent synchrotron emission observed: Implications for radio astronomy,' MNRAS, 317, 497-500
Blandford, R.D. & Königl, A. 1979, 'Relativistic jets as compact radio sources,' ApJ, 232, 34-48
Blandford, R. D. & Payne, D. G. 1982, 'Hydromagnetic flows from accretion discs and the production of radio jets,' MNRAS, 199, 883-903
Bower, G. C., Falcke, H., & Backer, D. C. 1999, 'Detection of Circular Polarization in the Galactic Center Black Hole Candidate Sagittarius A*,' ApJ, 523, L29-L32
Cawthorne, T. V., Wardle, J. F. C., Roberts, D. H., & Gabuzda, D. C. 1993, 'Milliarcsecond Polarization Structure of 24 Objects from the Pearson-Readhead Sample of Bright Extragalactic Radio Sources. II. Discussion,' ApJ, 416, 519-535
Celotti, A. & Fabian, A. C. 1993, 'The kinematic power and luminosity of parsec scale radio jets - an argument for heavy jets,' MNRAS, 264, 228-236
Fender, R., Rayner, D., Norris, R., Sault, R. J., & Pooley, G. 2000, 'Discovery of circularly polarized radio emission from SS433,' ApJ, 530, L29-L32
Hirotani, K., Iguchi, S., Kimura, M., & Wajima, K. 1999, 'Pair plasma dominance in the 3C279 jet on parsec scales,' PASJ, 51, 263-267
Hirotani, K., Iguchi, S., Kimura, M., & Wajima, K. 2000, 'Pair plasma dominance in the parsec-scale relativistic jet of 3C345,' preprint, astro-ph 0005394
Hodge, P. E., 1982, 'Circular polarization from compact extragalactic radio sources as a result of nonuniform magnetic fields,' ApJ, 263, 595-598
Homan, D. C. & Wardle, J. F. C. 1999, 'Detection and Measurement of Parsec-Scale Circular Polarization in Four AGN,' AJ, 118, 1942-1962
Jones, T. W. & O'Dell, S. L. 1977, 'Transfer of polarized radiation in self-absorbed synchrotron sources. I - Results for a homogeneous source,' ApJ214, 522-539
Jones, T. W. 1988, 'Polarization as a probe of magnetic field and plasma properties of compact radio sources,' ApJ, 332, 678-695
Kennett, M. & Melrose, D. 1998, 'Propagation-induced circular polarization in synchrotron sources' Publ. Astron. Soc. Aust., 15, 211-216
Komessaroff, M. M., Roberts, J. A., Milne, D. K., Rayner, P. T. & Cooke, D. J. 1984, 'Circular and linear polarization variations of compact radio sources,' MNRAS, 208, 409-425
Laing, R. A. 1980, 'A model for the magnetic-field structure in extended radio sources,' MNRAS, 193, 439-449
Legg, M. P. C. & Westfold, K. C. 1968, 'Elliptic polarization of synchrotron radiation,' ApJ, 154, 499-514
Lovelace, R. V. E. & Romanova, M. M. 1995, 'MHD Formation of Jets from Accretion Disks,' in Energy Transport in Radio Galaxies and Quasars, ed. P. E. Hardee, A. H. Bridle, & J. A. Zensus, A.S.P. Conference Series, 100, 25-30
Macquart, J.-P. & Melrose, D. B. 2000, 'Circular polarization induced by scintillation in a magnetized medium,' ApJ, in press
Macquart, J.-P., Kedziora-Chudczer, L., Rayner, D. P., & Jauncey, D. L. 2000, 'Strong, Variable Circular Polarization in PKS 1519-273,' ApJ, 538, 623-627
Margon, B. & Anderson, S. F. 1989, 'Ten years of SS 433 kinematics,' ApJ, 347, 448-454
Paragi, Z., Vermeulen, R. C., Fejes, L., Schilizzi, R. T., Spencer, R. E., & Strirling, A. M. 1999, 'The inner radio jet region and the complex environment of SS433,' A&A, 348, 910-916
Rees, M. J. 1984, 'Black hole models for active galactic nuclei,' Ann. Rev. Astron. Astrophys. 22, 471-506
Rayner, D. P., Norris, R. P., & Sault, R. J., 2000, 'Radio circular polarization of active galaxies,' MNRAS, in press.
Rayner, D. P., 2000, Ph.D. Thesis, University of Tasmania.
Reynolds, C. S., Fabian, A. C., Celotti, A. & Rees, M. J. 1996, 'The matter content of the jet in M87: evidence for an electron-positron jet,' MNRAS, 283, 873-880
Taylor, G. B. 1998, 'Magnetic Fields in Quasar Cores,' ApJ, 506, 637-646
Wardle, J. F. C. 1998, ‘Magnetic Fields in AGN,’ in Radio Emission from Galactic and Extragalactic Compact Sources, ASP Conference Series, Vol. 144, IAU Colloquium 164, J.A. Zensus et al., (ed.), (ASP, San Francisco) 97-103
Wardle, J. F. C., Homan, D. C., Ojha, R., & Roberts, D. H. 1998, ‘Electron-Positron Jets Associated with the Quasar 3C 279,’ Nature 395, 457-461
Weiler, K. W. & de Pater, I. 1983, 'A catalog of high accuracy circular polarization measurements' Ap.J.Supplement, 52, 293-327