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CIRCULAR REPOLARIZATION IN COMPACT RADIO SOURCES

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SUMMARY

Generation of circular polarization in the process of transfer of radiation within a compact source, due to the presence of relativistic electrons, is discussed. The interpretation of the observations of polarization of compact radio sources in terms of this mechanism (called 'circular repolarization') yields the values of 1–10 for the lower limit of the ratio of relativistic to cold electron densities.

The principal results of measurements of circular polarization of compact flat spectrum objects can be summarized as follows (**1**)–(**8**).

(i) The linear and circular polarizations are not correlated. The highest degree of circular polarization normally measured is 0·4 per cent, although in the variable source BL Lac it reaches at times 2 per cent.

(ii) Circular polarization generally increases with decreasing frequency ν, seemingly steeper than $\nu^{-1/2}$ in some sources with simple (one component) intensity spectra; the errors of measurements are, however, too large to discuss the frequency dependence with any degree of certainty.

(iii) Circular polarization is generally too high to be explained as due to synchrotron radiation in an optically thin source with not too highly anisotropic distribution of electron pitch angles (**9**)–(**11**) (in the sense that magnetic fields computed from the polarization are usually so high as to cause a turnover in the intensity spectrum through synchrotron self-absorption at a considerably higher frequency than is actually observed).

(iv) At least one source (PKS 2134+004), which has a simple intensity spectrum, has circular polarization rising with decreasing frequency below the turnover. This is difficult to explain in terms of optical depth effects in a synchrotron source (**12**) unless the source is highly non-uniform in its polarization structure, the non-uniformity not being reflected in the intensity spectrum in the relevant range of wavelengths (**13**).

(v) Circular polarization seems to be variable in some sources of variable intensity.

Although the above results refer to measurements of integrated polarization, they hold for sources with simple, one-component intensity spectra; it is this type of source that we will discuss in what follows.

The property (iii) could, in principle, be accounted for by assuming high anisotropy in the pitch angle distribution of electrons (significant over the angle of the order of $1/\mathscr{E} = mc^2/E$, where E stands for the total electron energy. This assumption will not, however, alleviate the difficulty (iv). Both effects (iii) and (iv) can be understood if one invokes an additional mechanism, the contribution of which to circular polarization is dominant over synchrotron mechanism. The propagation effects in the plasma (cold and relativistic) within the source provide such a mechanism; in this communication we will examine some consequences of the suggestion, made in (**13**), that a substantial part of the observed circular polarization may be due to the Faraday pulsation effect (**14**) contributed by the relativistic electrons within the source. If there are enough thermal and low energy relativistic electrons in a source, the elliptically polarized (**15**) modes of propagation of electromagnetic waves in the source's plasma will be close to circularly polarized. The Faraday pulsation (i.e. the conversion of linear and circular polarizations (**14**)) of the waves then takes place only to the extent permitted by the deviation from circularity of the propagation modes, which is a function of relativistic and cold electron densities (**17**). In order to describe the small values of the observed circular polarization we will assume that we have enough cold and low energy relativistic electrons within the source to make the contribution of relevant relativistic electrons to the propagation effects small (which does not necessarily imply that the density of the former is large compared with that of the latter electrons, as we will see further on). In the transfer equations (**16, 17**) for I, Q and U, we can therefore neglect the propagation effects of relativistic electrons as well as those due to elliptically polarized absorption. This approximation limits the consideration of the Faraday pulsation effect to the conversion of linearly polarized radiation into circular, since the inverse process will not take place until the Stokes parameter V becomes comparable with other parameters, which is outside the present approximation determined by the small values of measured circular polarization. The more general solution of the transfer of synchrotron radiation in a mixture of relativistic and cold plasma and its discussion will be the subject of another paper (**18**). At present we will consider only the order of magnitude consequences of the interpretation of the circular polarization measurements of compact sources within the framework of this effect, which we will call for brevity circular repolarization, as it increases the degree of circular polarization with increasing path length within the source. The transfer equation for the Stokes parameter V will have the approximate form

$$dV/ds \cong \epsilon_V + \Delta k_r U, \tag{1}$$

for the case of an optically thin medium of small absorption. The notation is usual, ϵ_V being the emission coefficient for circular polarization, s the path length and Δk the diagonal element of the Hermitian part of the transfer tensor (which is related to the dielectric susceptibility tensor of the relativistic plasma (**16, 17**)):

$$\Delta k_r = -8{\cdot}5\times 10^{-3}\,\frac{2}{\gamma-2}\left[\left(\frac{\nu}{\nu_L}\right)^{(\gamma-2)/2}-1\right] \times(\gamma-1)(2{\cdot}9\times 10^6)^{(\gamma+2)/2}\,N_r\mathscr{E}_L(H\sin\theta)^{(\gamma+2)/2}\,\nu^{-(\gamma+4)/2}. \tag{2}$$

It is assumed that the distribution of relativistic electrons is isotropic and of the power-law type with the index γ, extending from the lower limit given by the Lorentz factor $\mathscr{E}_L$. H is the magnetic field, θ the angle between the field and the line of sight, ν_L is the critical frequency of electrons with $\mathscr{E}_L$, and N_r is the number density of relativistic electrons. We can take the solution for U appropriate for a source in which the Faraday dispersion is a dominant polarization effect:

$$U \cong \frac{\epsilon_Q}{2\beta}(1-\cos 2\beta s), \tag{3}$$

where ϵ_Q is the emission coefficient in Stokes parameter Q and 2β is the Faraday rotation coefficient due to both thermal and relativistic plasma (subscripts c and r, respectively)

$$2\beta = 2\beta_c + 2\beta_r \simeq -5\times 10^4 \left(N_c + N_r \frac{\gamma-1}{\gamma+1}\frac{\ln \mathscr{E}_L}{\mathscr{E}_L^2}\cot\theta\right)\frac{H\sin\theta}{\nu^2}. \tag{4}$$

N_c and N_r are the appropriate electron number densities. Integrating (1) with (3) and using the usual optically thin solution for I, we have for the degree of circular polarization

$$\Pi_V \cong \frac{\epsilon_V}{\epsilon_I} + \frac{\Delta k}{2\beta}\frac{\epsilon_Q}{\epsilon_I}\left(1 - \frac{\sin 2\beta s}{2\beta s}\right), \tag{5}$$

where ϵ_I is the emission coefficient in intensity. The first term in this equation describes the well known optically thin synchrotron emission effect (**9**)–(**11**). The second and third terms describe the circular repolarization effect. For $\beta s \gtrsim 1{\cdot}5$ the oscillating term can be neglected for order of magnitude considerations. Note that the oscillating term in circular repolarization depends on the argument $2\beta s$, while the Faraday depolarization depends on the argument βs. There is therefore a range of Faraday depths for which repolarization is substantial while depolarization (of linearly polarized radiation) is still not very large. Assuming, as is required by (iii) and (iv), that repolarization dominates over synchrotron emission of circular polarization, one can neglect the first term in equation (5). Then for $\beta s \gtrsim 1{\cdot}5$ and for $\gamma = 2$ one has

$$\Pi_V \cong \frac{\Delta k}{2\beta}\frac{\epsilon_Q}{\epsilon_I} = 10^6 \ln\frac{\nu}{\nu_L}\,\mathscr{E}_L \frac{N_r}{N_c}\frac{H\sin\theta}{\nu}. \tag{6}$$

It is easy to write appropriate expressions for other values of γ. For simplicity, all the following expressions will be written for $\gamma = 2$.

The following predictions could be confronted with the observational data. We emphasize again that they are valid for sufficiently homogeneous, simple, optically thin sources in which the effects of superposition of radiation from components with different properties is not dominant.

(i) The frequency dependence of the degree of circular polarization is in general steeper than $\nu^{-1/2}$. For $\gamma \geqslant 2$ it is proportional to ν^{-1}, while for $\gamma < 2$ and large ν/ν_L it is proportional to $\nu^{-\gamma/2}$. Observations suggest frequency dependence steeper than $\nu^{-1/2}$ for simple sources like PKS 2134+004 and PKS 0237−23 but the errors of measurements are large.

(ii) The degree of circular polarization should not be correlated with that of linear polarization. Indeed the ratio

$$\frac{\Pi_L}{\Pi_V} \lesssim 2\times 10^{-11}\frac{\nu^3}{\ln(\nu/\nu_L)} N_r^{-1}\mathscr{E}_L^{-1}(H\sin\theta)^{-2}s^{-1} \tag{7}$$

depends on parameters which can vary substantially from source to source. The lack of such correlation in the observational data has been noted.

(iii) The ratio Π_L/Π_V at some optically thin frequency ν should be correlated with the frequency ν_1 of the synchrotron self-absorption turnover. Eliminating s between (7) and the appropriate expression for ν_1 (e.g. equation following 3·53 in (**19**)) we have

$$\frac{\Pi_L}{\Pi_V} \gtrsim \text{const}\;\nu_1^{-3}; \tag{8}$$

the dependence on parameters $\mathscr{E}_L$ and H being weak for γ close to 2. There are too few simple sources observed for polarization to discuss the existence of this correlation now.

Although the observational data on circular polarization are too scarce to confirm or reject the circular repolarization mechanism at present, we will examine some consequences of such a mechanism for compact sources. The measurement of circular polarization yields information on $\mathscr{E}_L N_r N_c^{-1} H \sin\theta$. The magnetic field can be determined through the synchrotron self-absorption turnover theory. The product $\mathscr{E}_L N_r N_c^{-1}$ is of order 10^3 for PKS 2134+004 and 10^5 for PKS 0237—23. Assuming that there are no 'irrelevant' relativistic electrons (i.e. that the critical frequency corresponding to the cut-off energy $\mathscr{E}_L$ is equal to the turnover frequency) we get N_r/N_c of the order of 1 and 10, respectively, for these two sources. The ratios will be higher if such electrons are present.

Finally let us remark that observations of linear polarization of compact sources support the above conclusions regarding the ratio of relativistic to thermal electron densities. It was pointed out (**13**) that the observed linear polarization is not compatible with the expected amount of depolarization in compact sources like PKS 2134+004, PKS 0237−23 and PKS 1148−00, on the assumptions that $N_r/N_c \leqslant 1$ and that the sources are not highly inhomogeneous (**13**). In the paper (**13**) the second assumption was questioned and it was supposed that compact sources have considerable structure; for example, that most of the polarization is produced in a thin shell around a completely depolarized core. It should be noted, however, that the polarization of the shell would have to be very high to contribute to a resulting polarization of a few per cent of the core-shell object. In the framework of the interpretation of circular polarization data presented here, one can retain the view of moderate homogeneity of a compact source accepting $N_r/N_c \gtrsim 1$.

With a more complete set of data on both linear and circular polarization of compact sources one will be able to estimate N_r, N_c and $\mathscr{E}_L$ separately.

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REFERENCES

(**1**) Gilbert, J. A. & Conway, R. G., 1970. *Nature*, **224**, 1011.
(**2**) Conway, R. G., Gilbert, J. A., Raimond, E. & Weiler, K. W., 1971. *Mon. Not. R. astr. Soc.*, **152**, 1P.
(**3**) Roberts, J. A., Ribes, J. C., Murray, J. D. & Cooke, D. J., 1972. *Nature Phys. Sci.*, **236**, 3.
(**4**) Berge, G. L. & Seielstad, G. A., 1973. *Astr. J.*, **77**, 810.
(**5**) Seaquist, E. R., 1969. *Astrophys. Lett.*, **5**, 111.
(**6**) Seaquist, E. R., 1971. *Nature Phys. Sci.*, **231**, 93.

(7) Seaquist, E. R., 1973. *Astr. Astrophys.*, **22,** 299.
(8) Seaquist, E. R., Gregory, P. C., Biraud, F. & Clarke, T. R., 1973. *Nature Phys. Sci.*, **242,** 20.
(9) Roberts, J. A. & Komesaroff, M. M., 1965. *Icarus*, **4,** 127.
(10) Legg, M. P. C. & Westfold, K. C., 1968. *Astrophys. J.*, **154,** 499.
(11) Sciama, D. W. & Rees, M. J., 1967. *Nature*, **216,** 147.
(12) Pacholczyk, A. G. & Swihart, T. L., 1971. *Astrophys. J.*, **170,** 405.
(13) Pacholczyk, A. G. & Swihart, T. L., 1973. *Astrophys. J.*, **179,** 21.
(14) Pacholczyk, A. G. & Swihart, T. L., 1970. *Astrophys. J.*, **161,** 415.
(15) Sazonov, V. N., 1969. *Soviet Phys. JETP*, **29,** 578.
(16) Sazonov, V. N., 1969. *Sov. Astr.*, **13,** 396.
(17) Pacholczyk, A. G., 1973. Polarization of radio sources in *Proceedings of the IAU Colloquium No.* 23 *on Astronomical Polarimetry*, ed. T. Gehrels, University of Arizona Press, Tucson.
(18) Pacholczyk, A. G. & Swihart, T. L., 1973. In preparation.
(19) Pacholczyk, A. G., 1970. *Radio astrophysics: nonthermal processes in galactic and extragalactic sources*, W. H. Freeman & Co, San Francisco.