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CIRCULAR POLARIZATION OF COMPACT, EXTRAGALACTIC RADIO SOURCES. I. SYNCHROTRON EMISSION AND CIRCULAR REPOLARIZATION

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ABSTRACT

We suggest that the observed circular polarization of compact extragalactic radio sources is due to both a synchrotron emission mechanism and circular repolarization in the process of quasi-longitudinal propagation of radiation through the radio sources' plasmas. The addition of circular repolarization eliminates some of the difficulties in assuming synchrotron emission as the only mechanism for the observed circular polarization reported in the Weiler and de Pater catalog.

Subject headings: polarization — radiation mechanisms — radio sources: galaxies

I. INTRODUCTION

Earlier investigations of circular polarization of compact extragalactic radio sources (see, for example, Roberts *et al.* 1975) interpreted their results simply in terms of the intrinsic polarization of synchrotron emission. This approach has not been particularly successful, and other sources of circular polarization have been sought. Pacholczyk and Swihart (1973, 1974) have suggested that propagation effects (Sazonov 1969) may better explain observed circular polarization data. Jones and O'Dell (1977*a*) and Burbidge, Jones, and O'Dell (1974) discussed propagation effects and also suggested relativistic bulk motion effects as a source of discrepancy between intrinsic and observed circular polarization. Jones and O'Dell (1977*b*) and Hodge (1982) investigated the effects of nonuniformities in the source's structure on circular polarizations. The scarcity of available data, in particular those referring to different frequencies, did not allow any definite conclusion as to the origin of the observed circular polarization. Circular polarization measurements of extragalactic sources are difficult because this polarization is extremely small—no known source has greater than about 0.5% of its total intensity in circular polarization. Recently, Weiler and de Pater (1983) published a comprehensive catalog of "high-accuracy" circular polarization measurements containing results obtained before mid-1982. "High accuracy" was defined there to mean a quoted standard error of better than 0.1%. This catalog includes 123 sources with a total of fewer than 600 individual measurements. The purpose of this paper is to analyze the data in Weiler and de Pater (1983) in the light of the two mechanisms of generation of circular polarization: synchrotron emission mechanism, and circular repolarization due to quasi-longitudinal propagation of radiation through the radio source's plasma.

II. THE OBSERVATIONAL MATERIAL

Of the 123 objects in the Weiler and de Pater (1983) catalog, only those with adequate data and simple intrinsic characteristics are analyzed. The following criteria are used in selecting the sample.

1. Detection error.—Only objects with a measured degree of circular polarization larger than two standard deviations are considered.

2. Angular size.—Compact objects with angular sizes of less than a few milliarcseconds or linear sizes of less than 10 pc are selected to avoid complex multicomponent structures.

3. Number of measurements.—Objects with measurements at three or more different frequencies are used to allow an attempt at describing the frequency dependence of polarization.

4. Low variability of flux or linear polarization or both.—Since there are only a few objects which satisfy the above criteria, we include objects which have data of different frequencies at different epochs, provided their flux densities or linear polarizations or both do not vary more than a few per cent between the epochs of measurements.

5. Spectral structure.—Objects with single-component spectra should be used, as multiple components may lead to confusion about the relative contribution to circular polarization from each component. Since there are only a few sources which will satisfy all five criteria, we also include objects with complex spectral form if they satisfy the other four criteria, and it appears that their other components do not significantly affect the observed radiation from the compact component.

These selection criteria leave us with only eight sources in our final sample. These sources are: 0237−233, 0316+413, 0831+557, 1127−145, 1253−055, 2134+004, 2145+067, and 2230+114. Of the eight sources, only four have measurements close in time and frequency that allow any modeling. We would encourage future, simultaneous, multifrequency, circular polarization measurements, which are extremely useful for interpretation of physical characteristics.

III. SYNCHROTRON EMISSION MECHANISM

If the measured circular polarization of a simple one-component source were due to synchrotron emission, its amount and its frequency dependence should fulfill the following conditions, which can be considered as a test for the synchrotron origin of the polarization.

1. The amount of the observed circular polarization should be compatible with the value of the magnetic field H_s derived from the observed spectral turnover of total intensity under the (generally accepted) assumption that this turnover is due to synchrotron self-absorption. Spectral intensities are taken from Kuehr *et al.* (1981). In the sample of sources considered here, only the two objects 2134+004 and possibly 1253−005

TABLE 1

SUMMARY OF FITTED MODELS

Object	ν_{to} (GHz)	S	C_{17}	Fit	P_1 σ_{P_1}	P_2 σ_{P_2}	χ^2	N_r/N_c σ_{N_r/N_c}	H_v σ_{H_v} (G)	H_s σ_{H_s} (G)	$H_{v'}$ $\sigma_{H_{v'}}$ (G)
0237−233......	1.1	3.0	0.23	a	4.8(−2)	4.5(−1)	5.08	83	5.7(−5)	3.0(−5)	3.2(−3)
					3.5(−3)	5.4(−3)		19	8.3(−6)	1.3(−5)	1.7(−3)
				b	6.1(−2)	3.3(−1)	4.78	60	9.4(−5)	...	...
					3.8(−2)	4.9(−2)		16	1.1(−4)	...	...
0316+413......	6.0	1.5	0.42	c	−5.1(−2)	−3.8(−2)	0.05	1	7.4(−4)	6.9(−4)	1.1(−2)
					1.7(−3)	2.0(−3)		0.1	4.9(−5)	8.0(−5)	6.9(−3)
0831+557......	1.2	4.2	0.18		...	...	...	...	...	4.6(−7)	4.1(−5)
					...	...	...	...	...	1.8(−7)	2.1(−5)
1127−145......	2.0	2.3	0.29	d	3.8(−2)	−3.6(−1)	...	59	4.8(−5)	3.7(−5)	2.2(−3)
					1.2(−2)	2.7(−2)	...	11	3.1(−5)	1.3(−5)	1.3(−3)
1253−055......	4.8	1.8	0.36		...	...	...	...	...	8.7(−4)	9.5(−3)
					...	...	...	...	...	2.0(−4)	6.5(−3)
2134+004......	6.5	2.3	0.29	e	3.9(−2)	5.6(−1)	...	10	6.0(−4)	3.2(−3)	2.0(−3)
					9.9(−3)	2.2(−2)	...	1	3.0(−4)	8.5(−4)	6.1(−4)
				f	3.1(−2)	5.3(−1)	...	10	3.9(−4)	...	...
					1.0(−2)	1.6(−2)	...	1	2.5(−4)	...	...
2145+067......	4.8	1.3	0.49		...	...	...	...	...	3.4(−4)	8.5(−3)
					...	...	...	...	...	5.5(−5)	1.4(−3)
2230+114......	0.8	2.0	0.32		...	...	...	...	...	2.5(−5)	5.2(−4)
					...	...	...	...	...	2.9(−6)	5.2(−4)

NOTES.—Parentheses enclose powers of factor 10. There is only one degree of freedom in the fits to a, b and c, due to scarcity of data.

seem to fulfill this condition. Object 2230+114 has the largest scattering in values of the magnetic field $H_{\nu'}$ (see Table 1), indicating the effect of possible time variability, which dominates the rest of the Weiler and de Pater (1983) catalog. On average, the value of $H_{\nu'}$ derived from the magnitude of circular polarization is larger by a factor of 25 than that derived from the spectral turnover (see Fig. 1). This excess magnetic field suggests that part of the observed circular polarization comes from mechanisms other than synchrotron radiation (such as, for example, circular repolarization). The discrepancy between intrinsic and observed circular polarization may also be explained by the bulk relativistic motion of source components (see, e.g., Jones and O'Dell 1977*a*; Burbidge, Jones, and O'Dell 1974). However, such activity may not be present in simple single-component sources (e.g., 0237−233, 1127−145, and 2230+114 in our sample) which also have observed excess magnetic field.

2. The synchrotron mechanism of circular emission implies a reversal of sign of circular polarization in the spectral vicinity of the spectral self-absorption turnover, the zero-crossing frequency of circular polarization being about one-half the turnover frequency (ν_{to}). In our sample of sources only one object (0316+413) shows a definite zero-crossing frequency (at about 2 GHz, while its spectrum turns over at 6 GHz). The trend of circular polarization data on 0237−233 might be suggestive of a projected zero-crossing frequency at 0.5 GHz while its spectrum is turned over at 1.1 GHz. However, either the remaining objects in our sample do not have a projected zero-crossing frequency in agreement with the turnover frequency; or the zero-crossing frequency cannot be predicted, due to too few data points. Circular repolarization, the conversion of linear polarization into circular polarization within the source, would also have a similar zero-crossing frequency, because the linear polarization of such a synchrotron source exhibits a similar sign flip, which in turn forces any conversion of circular polarization into opposite modes. The absence of such a sign change may imply complex source structure or inhomogeneity (see, e.g., Jones and O'Dell 1977*a*, *b*). With the quantity and quality of the existing data, we still cannot say for sure that there is no such zero crossing in circular polarization for most of the objects. The absence of such a zero-crossing frequency could be checked with simultaneous multifrequency VLBI observations; furthermore, such observations will be helpful to serve as a check to existing detailed theoretical models of extragalactic radio sources.

3. The circular polarization of synchrotron emission has a characteristic $\nu^{-1/2}$ frequency dependence. In the sample of objects analyzed here, this dependence does not seem to represent the observed data very well. Only for two sources (0237−233 and 2134+004) is the agreement adequate. As has been discussed by others (e.g., Pacholczyk and Swihart 1974; Roberts *et al.* 1975; Jones and O'Dell 1977*a*), most data suggest a frequency dependence steeper than $\nu^{-1/2}$, thus implying an additional component of circular polarization of frequency dependence steeper than $\nu^{-1/2}$; and circular repolarization is one such candidate.

The above tests for the synchrotron origin of the observed circular polarization are not satisfied together by any of the objects discussed here, although three of the objects seem to pass two tests each. Data on 2134+004 show agreements in both magnetic field and frequency dependence, but the zero-crossing frequency predicted at 3 GHz is not observed. 0316+413 has good agreement in the zero-crossing frequency of circular polarization but has scattered data points between 5 and 9 GHz which no $\nu^{-1/2}$ curve could fit, and the magnetic fields disagree by a factor of 100. 0237−233 shows a relatively good $\nu^{-1/2}$ dependence and a correct projected zero-crossing frequency, but its magnetic fields disagree again by a factor of 100. It should therefore be concluded that not a single object in the sample studied exhibits circular polarization whose origin could be ascribed entirely to the synchrotron emission process; it seems rather likely that a significant additional component of circular polarization, monotonically varying with frequency, is present in the radiation from these sources.

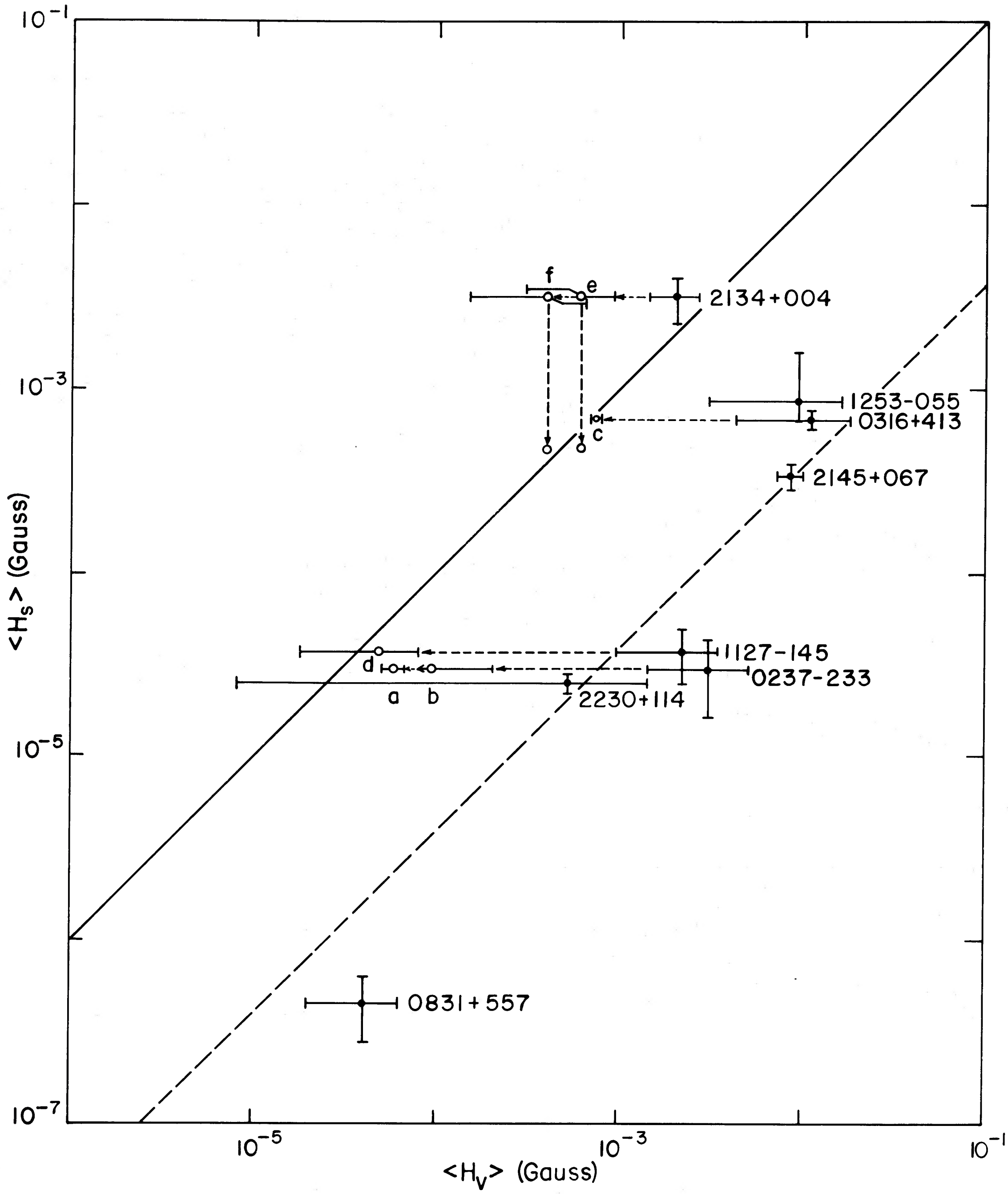

FIG. 1.—Magnetic fields of compact extragalactic radio sources derived from synchrotron self-absorption turnover (H_s) and circular polarization of synchrotron emission (H_v). Filled circles represent the values of the magnetic field derived from raw circular polarization data, open circles those derived from the parameter P_1 (eq. [2]). Solid line represents $H_v = H_s$, while broken line represents $H_v = 25H_s$, the best fit to all objects except 2134+004. Symbols a, b, c, d, e, and f correspond to different data of same (or close) epoch selected in the analysis (see Table 2 for details).

IV. CIRCULAR REPOLARIZATION MECHANISM

We assume now that the excess circular polarization mentioned in § III as present in the sample of compact sources discussed here is due to conversion of linear into circular polarization in the process of transfer of (predominantly linearly) polarized synchrotron radiation throughout the radio source. This process, called circular repolarization, was described in the quasi-longitudinal approximation in a magnetoactive thermal plasma as resulting from the presence of an admixture of relativistic (synchrotron-emitting) electrons by Pacholczyk (1973) and Pacholczyk and Swihart (1974). The small circularly polarized component generated during the propagation has a ν^{-1} frequency dependence throughout the optically thin and thick (to synchrotron absorption) regimes, with a change in sign at about one-half the synchrotron self-absorption turnover frequency, for sources with electron energy distribution characterized by an index $S \gtrsim 2$. The amount of the polarization depends on the relative amount of relativistic and thermal electron densities and on the low energy cutoff in the relativistic electron distribution.

Detailed theoretical calculations can be found in Jones and O'Dell (1977*a*) for homogeneous sources and in Jones and O'Dell (1977*b*) for inhomogeneous sources. For a large Faraday depth, the conversion of circular polarization is important and the observed circular polarization will be approximated by

$$\Pi_v(\text{observed}) = P_1 v^{-1/2} + P_2 v^{-1} , \quad (1)$$

where v is frequency in GHz. Equation (1) is identical with the third line of equation (13) in Jones and O'Dell (1977*a*). More specifically, we assume that the observed degree of circular polarization Π_v at a frequency v is due to a combination of synchrotron emission $P_1 v^{-1/2}$ and circular repolarization $P_2 v^{-1}$. Since the data chosen for our analysis are within a small frequency range, in either optically thick or thin regimes where the sign reversal does not take place equation (1) is sufficient to model the data until the data are improved both qualitatively and quantitatively in the future. The polarization parameters P_1 and P_2 are derived from the best fit to the data for each source in the sample. From the synchrotron parameter P_1 a magnetic field H_v can be estimated,

$$H_v = \left[\frac{P_1/100C}{400(S+2)}\right]^2 \times 10^9 \text{ G} , \quad (2)$$

where $C = 1$ in the optically thin region and $C = C_{17}$ in the thick region, C_{17} being given and tabulated in Pacholczyk (1976). The repolarization parameter P_2 yields the lower limit

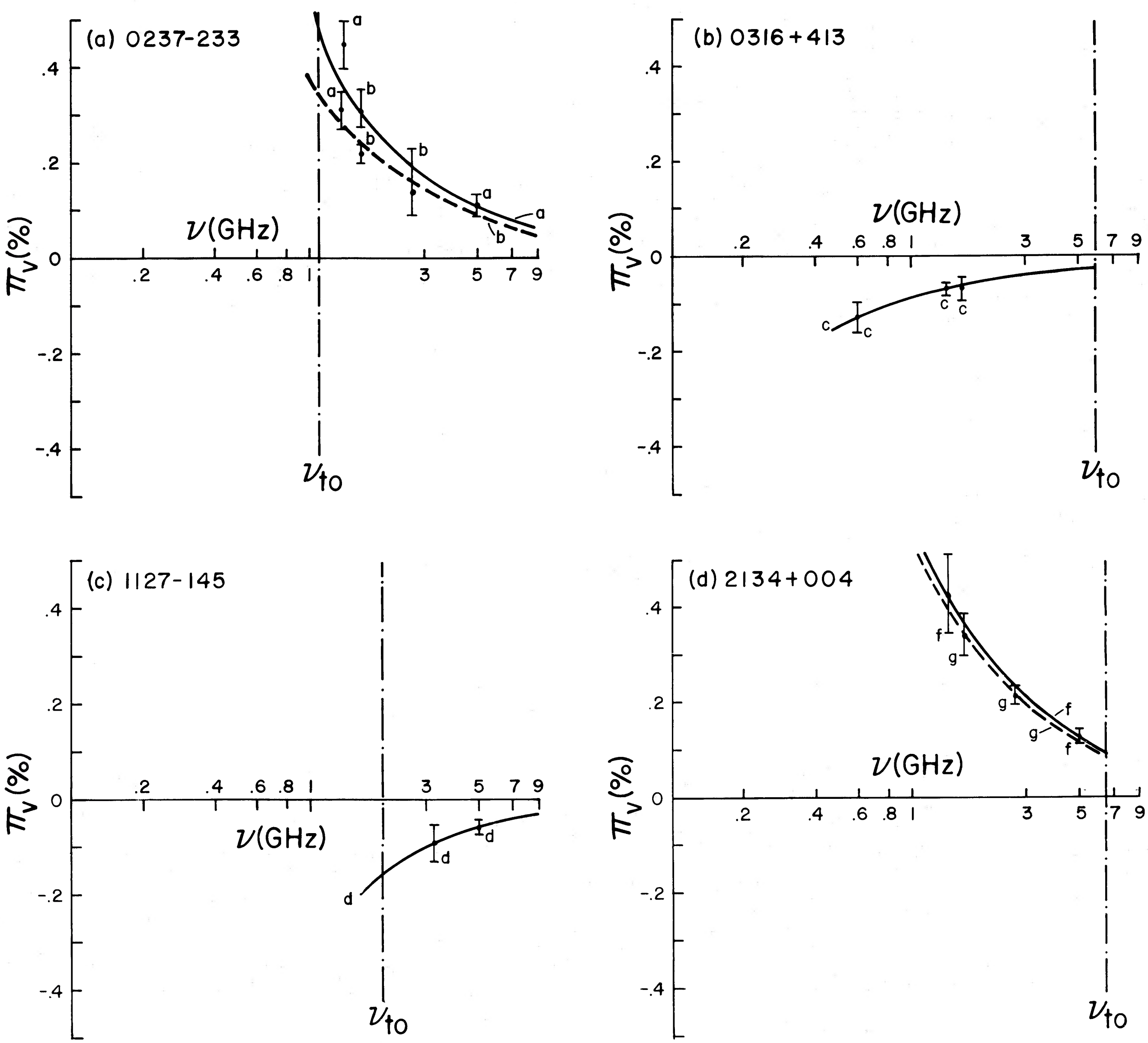

FIG. 2.—Circular polarizations of compact extragalactic radio sources: a two-component model, synchrotron emission, and circular repolarization. Broken lines represent the best fitted models to the data. Vertical dot-dash lines indicate the synchrotron self-absorption turnover frequencies. Symbols a, b, c, d, e, and f correspond to different data of same (or close) epoch selected in the analysis (see Table 2 for details).

TABLE 2

SUMMARY OF DATA SELECTED IN MODEL FITTING

Fit	Object	Epoch	ν (GHz)	Π_υ	σ_{Π_υ}
a	0237−233	1971.06	1.39	+0.311%	0.04%
		1971.10	1.42	+0.448	0.05
		1971.09	5.0	+0.111	0.025
b	0237−233	1975.02	1.666	+0.315	0.038
		1975.09	1.666	+0.219	0.022
		1975.06	2.7	+0.158	0.07
c	0316+413	1974.06	0.61	−0.128	0.033
		1971.11	1.415	−0.068	0.014
		1975.02	1.666	−0.067	0.025
d	1127−145	1971.01	3.24	−0.09	0.04
		1971.09	5.0	−0.055	0.015
e	2134+004	1971.10	1.42	+0.429	0.085
		1971.09	5.0	+0.13	0.014
f	2134+004	1976.08	2.7	+0.217	0.02
		1975.09	1.666	+0.345	0.045

of the ratio of the relativistic N_r to the thermal N_c electron densities

$$\frac{N_r}{N_c} \geq \frac{P_2}{H^{1/2}} \tag{3}$$

(cf. eq. [15] in Pacholczyk and Swihart 1974 with the low-energy cutoff pitch angle $\sin\theta \approx 1$ and the cutoff frequency $\nu_L \approx 10^{-3}\nu$).

The values of the polarization parameters P_1 and P_2, obtained from the least-squares fit of equation (1) to the available data, and the derived parameters H_υ and N_r/N_c (eqs. [2] and [3]) together with their statistical precision and goodness of fit are listed in Table 1. Some of the parameters are derived from only two data points (see Table 2 for the actual data) and do not, in a sense, have any statistical meaning. That is why we do not report their corresponding χ^2 values. The parameters are reported as crude estimates of the excess circular polarizations; together with other parameters derived with more than two data points, they seem to form a relatively well described picture in which circular repolarization does exist in extragalactic radio sources. In Figure 2, we show the model in broken lines and the actual data points used to fit the model. More simultaneous multifrequency observations in the future will allow better predictions.

V. CONCLUSIONS

From the results summarized in Table 1, the following conclusions can be drawn.

1. The results obtained at different epochs for the same sources are compatible and lead to very similar values for the magnetic field H_υ and the ratio of electron densities N_r/N_c.
2. The values of the magnetic field H_υ obtained from the synchrotron parameter P_1 (eq. [2]) are in excellent agreement with the values of the magnetic field H_s derived from the synchrotron self-absorption turnover.
3. The fit of data to equation (1) is good regardless of whether data points refer to optically thin or thick regimes.
4. The lower limits to the electron density ratios N_r/N_c are between 1 and 100 and seem to be inversely related to the values of the magnetic field, suggesting higher relativistic electron energy losses for sources with stronger magnetic field.

In sum, the hypothesis that circular repolarization significantly contributes to the observed circular polarization of synchrotron-emitting compact sources agrees well with the existing polarization measurements of these sources. Any further discussion of these mechanisms in compact radio sources requires a substantial increase in observational material. Our sample does not include highly variable sources. Such sources will be modeled by a time-varying model in a forthcoming paper.

REFERENCES

Burbidge, G. R., Jones, T. W., and O'Dell, S. L. 1974, *Ap. J.*, **193**, 43.
Hodge, P. E. 1982, *Ap. J.*, **263**, 595.
Jones, T. W., and O'Dell, S. L. 1977*a*, *Ap. J.*, **214**, 522.
———. 1977*b*, *Ap. J.*, **215**, 236.
Kuehr, H., Witzel, A., Pauliny-Toth, I. I. K., and Nauber, U. 1981, *Astr. Ap. Suppl.*, **45**, 367.
Pacholczyk, A. G. 1971, *M.N.R.A.S.*, **153**, 3P.
———. 1973, *M.N.R.A.S.*, **163**, 29.
———. *Radio Galaxies: Radiative Transfer, Dynamics, Stability and Evolution of a Synchrotron Plasmon* (Oxford: Pergamon), 1976.
Pacholczyk, A. G., and Swihart, T. L. 1971., **170**, 405.
———. 1973, *Ap. J.*, **179**, 21.
———. 1974, *Ap. J.*, **192**, 591.
Roberts, J. A., Roger, R. S., Ribes, J. C., Cooke, D. J., Murray, J. D., Cooper, B. F. C., and Biraud, F. 1975, *Australian J. Phys.*, **28**, 325.
Sazonov, V. N. 1969, *Astr. Zh.*, **46**, 502.
Weiler, K. W., and de Pater, I. 1983, *Ap. J. Suppl.*, **52**, 293.

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