

THE POLARIZATION OF SEYFERT GALAXIES

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ABSTRACT

We have measured the optical linear polarization of 99 Seyfert galaxies. Several highly polarized objects have been discovered and are discussed elsewhere. However, most Seyferts have very little polarization, $p \leq 0.5\%$, and much of this might be produced by foreground dust in the Galaxy; thus the occurrence of substantial intrinsic polarization is quite rare. Some significant similarities and differences between Seyfert and QSO polarization are discussed. A few measurements for narrow emission line galaxies are also presented.

Subject headings: galaxies: Seyfert — polarization — quasars

I. INTRODUCTION

We report some results and implications of a survey of the optical linear polarization of Seyfert galaxies. This survey was begun soon after Angel *et al.* (1976) had shown that the polarization of NGC 1068 was caused by dust, and was not, as previously interpreted, of nonthermal origin. One of the aims of the survey was to find other highly polarized Seyfert galaxies whose polarization (including the circular component) could then be examined in more detail to investigate the polarization mechanism. This aim was achieved, and data for individual objects are discussed in earlier publications and in a forthcoming summary (Thompson *et al.* 1983). Our survey was undertaken with the impression that polarization in Seyfert galaxies might be a common phenomenon, but one of the principal findings to be discussed (§ IV) is that the large majority of Seyfert galaxies have little intrinsic optical polarization ($p < 0.2-0.5\%$).

Another goal was to compare the polarization properties of Seyfert nuclei and QSOs, Stockman and Angel (1978) and Stockman (1978) having already reported on a survey of the polarization of QSOs. Although many properties of QSOs and Seyfert galaxies suggest some connection in the underlying phenomenon (e.g., Weedman 1977), this concept of continuity is not bolstered by comparison of optical polarization (§ IVa, d). High polarization in QSOs has a nonthermal origin whereas in Seyfert galaxies dust is often responsible.

When correction is made for foreground Galactic interstellar polarization, most Seyfert galaxies might be intrinsically unpolarized whereas many QSOs show a significant residual intrinsic polarization, $p \approx 0.6-1\%$ (§ IVd).

The observational program and results are presented in § II and § III, respectively; § V touches on some clues to the origin of the intrinsic polarization, including variability and alignment with radio structure. In the course of this survey we also acquired polarimetric data for several narrow emission line galaxies (§ VI) which indicate that further study of this class of object should be pursued.

II. OBSERVATIONS

The survey was made using a variety of two-channel photoelectric Pockels cell polarimeters, based on the design of Angel and Landstreet (1970). An observation consisted of a measurement of the Stokes parameters $Q = p \cos(2\theta)$ and $U = p \sin(2\theta)$, where p is the polarization and θ is the position angle. All observations have been corrected for night-sky polarization, and for instrumental efficiency. Observations of interstellar polarization and null standards (Serkowski 1974) were obtained to reduce the position angles to the standard equatorial system and to check for instrumental polarization. Quoted errors in the polarization are from photon counting statistics, and the assigned error for a

polarization $p = (Q^2 + U^2)^{1/2}$ is $\sigma_p = (\sigma_Q + \sigma_U)/2$. The observations were made such that $\sigma_Q \approx \sigma_U$. The error in position angle is $\sigma_\theta = 28.65 \sigma_p/p$ for $\sigma_p < p$ and nominally 52° otherwise (Serkowski 1962).

The observations were made, for the most part, with a Corning 4-96 filter (3800–5600 Å). This filter was chosen for two reasons. As mentioned in the introduction, early observations of Seyfert polarization were interpreted as evidence for nonthermal flux. It was recognized that galactic starlight can dilute the observed polarization in the red region of the spectrum, and so to maximize the signal-to-noise ratio of an observation a blue-green filter was used. When spectropolarimetric observations of NGC 1068 were obtained (Angel *et al.* 1976), it was found that the polarization is produced by dust scattering; the sharp increase in polarization into the blue is a result of increased dust scattering efficiency. Although the colors of NGC 1068 are very red, the maximum signal-to-noise ratio for NGC 1068 and similar galaxies is again achieved from observations obtained with a blue-green filter. A 4" aperture was used for all but a few of the observations to minimize the diluting effect of starlight from regions surrounding the Seyfert nuclei.

The observations were obtained from 1976 to 1982 on the Steward Observatory 2.3 m, the Las Campanas 1.0 and 2.5 m, the Kitt Peak 1.3 and 2.1 m, and the University of Western Ontario 1.2 m telescopes.

III. RESULTS

The results of the survey are presented in Table 1, which lists the galaxy name, a classification as type 1 or type 2 (Weedman 1977), the Julian date of the observation, the polarization and its error, the position angle and its error, and finally, notes concerning alternative designations, filters, or observing apertures.

The sample consists of 99 Seyfert galaxies, 17 of which have at least one repeat observation (§ Va). An initial sample of bright galaxies in the northern sky was selected from the list of Khachikian and Weedman (1974). Subsequent additions were made from the lists of Weedman (1977, 1978) and Huchra (1981, personal communication). Brightness was the main selection criterion, although, depending on available observing time, galaxies with redshifts $z \geq 14,000 \text{ km s}^{-1}$ were usually ignored in favor of nearer galaxies. We have observed 40% of the 230 Seyferts in Huchra's compilation as it existed in March of 1981.

Recent spectroscopic surveys have shown that the properties of Seyfert 2 galaxies and narrow emission line galaxies are very similar. Shuder and Osterbrock (1981) have proposed that the Seyfert phenomenon (perhaps defined as photoionization of the emitting gas by a power-law continuum) is present in those galaxies with line ratios $[\text{O III}] \lambda 5007/\text{H}\beta \approx 3$ and FWHM line

widths $\geq 300 \text{ km s}^{-1}$. Our sample contains two galaxies, Mrk 298 and NGC 7582, which do not meet these criteria. However, they are close to the region of power-law photoionization according to the emission line criteria of Baldwin, Phillips, and Terlevich (1981). Considering the uncertain nature of such definitions, we have included these galaxies in our analysis. Note also that Shuder (1980) and Véron *et al.* (1980) show that NGC 2110, NGC 2992, NGC 5506, and MCG –5–23–16 have broad components in the H α emission lines (FWZI $\geq 2500 \text{ km s}^{-1}$). They have been listed as Seyfert galaxies in Table 1.

Since the selection criteria are scarcely rigorous, it is worth mentioning two selection effects which might influence the observed frequency distribution of polarization (§ IV). First, the projected size of our fixed aperture on a galaxy is redshift dependent, and therefore so is the dilution of the intrinsic nuclear polarization by unpolarized stellar light. Furthermore, the intrinsic nuclear-to-galactic luminosity ratio need not be the same from galaxy to galaxy. This effect can be extreme: if NGC 1068 were at a redshift of 10^4 km s^{-1} and not its observed value of 1100 km s^{-1} , its measured polarization would be $\sim 0.5\%$ as opposed to the survey value of 2.11%. The second effect is that it would be more difficult to detect distant Seyfert galaxies with a technique which relies on observing a UV excess (e.g., the Markarian survey). Thus, distant Seyfert galaxies, to be detected, will have to be bluer or will have to have more luminous nuclei. This effect tends to offset the dilution of the polarization by galactic starlight. Because of the offsetting nature of the two effects, and the obvious difficulty of accurate corrections, we have not attempted to correct the data for stellar dilution.

IV. THE FREQUENCY DISTRIBUTION OF POLARIZATION

We wish to determine the frequency distribution of polarization for Seyfert galaxies. Simple histogram prepared from Table 1 are potentially misleading because of biases introduced by observational errors (σ) in the Stokes parameters; these are particularly pronounced for small p ($p \lesssim \sigma_p$) since p is a positive-definite quantity (with non-Gaussian errors). To discover the underlying frequency distribution, we use the iterative deconvolution scheme proposed by Lucy (1974), in its discrete, heterogeneous (in σ) form. The joint probability distribution required for application of this technique to polarization data is given, for example, by Serkowski (1962, eq. [64]). The data used are the first entries for each galaxy in Table 1. We present solutions obtained after four iterations (Fig. 1a). Solutions after more iterations, while quite similar, tend to emphasize even more the contributions of individual galaxies to ψ .

TABLE 1
 LINEAR POLARIZATION OBSERVATIONS OF SEYFERT GALAXIES

Object	Type	JD +2,440,000	p (%)	σ_p (%)	θ	σ_θ	Remarks
Mrk 1	2	3077	0.30	0.33	73.2	52.0	NGC 449
Mrk 3	2	2782	2.00	0.12	142.8	1.6	
		2783	1.82	0.11	144.8	1.6	
		3079	1.31	0.16	148.8	3.5	
Mrk 6	1	2783	0.54	0.15	141.2	8.0	9", IC 450
Mrk 9	1	2782	0.82	0.21	153.5	7.1	
Mrk 10	1	2782	0.32	0.20	23.0	18.1	
Mrk 34	2	3079	1.42	0.54	99.0	11.0	
		3278	1.12	0.22	56.6	5.7	7"4
Mrk 50	1	4786	0.60	0.16	88.4	7.7	
Mrk 78	2	3079	0.73	0.29	156.9	11.4	
Mrk 79	1	2923	0.34	0.19	0.4	16.2	
Mrk 141	1	3079	0.29	0.28	151.4	27.9	
Mrk 176	2	3279	0.54	0.16	146.3	8.2	7"4, no filter
Mrk 198	2	2921	0.32	0.23	11.8	20.9	
Mrk 231	1	2784	2.87	0.08	95.1	0.8	9"
Mrk 268	2	2922	0.86	0.42	18.6	13.7	
Mrk 270	2	2922	0.40	0.26	96.9	19.0	NGC 5283
Mrk 273	2	2921	0.37	0.44	66.7	52.0	
Mrk 279	1	3278	0.24	0.10	133.0	12.0	7"4, no filter
Mrk 290	1	2922	0.99	0.22	128.1	6.3	
Mrk 291	1	4781	0.55	0.17	80.9	8.5	
Mrk 298	2	4781	1.09	0.18	104.5	4.6	
Mrk 304	1	2921	0.98	0.14	136.6	4.2	
		3080	1.04	0.22	129.5	6.2	
Mrk 335	1	3077	0.48	0.11	107.6	6.9	
Mrk 348	2	3077	2.05	0.31	83.6	4.3	NGC 262
		3079	1.53	0.32	86.4	6.0	
Mrk 352	1	3077	1.11	0.23	143.9	5.8	
Mrk 372	2	3078	1.49	0.46	134.0	8.8	
Mrk 374	1	3079	0.64	0.32	159.8	14.2	
Mrk 376	1	2785	4.34	0.22	174.9	1.4	
		3078	4.65	0.20	177.4	1.2	
Mrk 463E	2	4783	4.18	0.16	85.5	1.1	
Mrk 478	1	2922	0.46	0.15	44.9	9.5	
Mrk 486	1	2923	3.40	0.14	136.8	1.2	
Mrk 506	1	2923	0.31	0.34	161.2	52.0	
Mrk 509	1	2923	1.14	0.09	148.8	2.2	
		3080	1.00	0.12	151.6	3.6	
		3280	0.78	0.11	152.7	4.1	5"2
		4347	1.09	0.15	146.5	4.0	
		4783	1.18	0.09	152.6	2.1	
Mrk 541	1	3077	0.54	0.47	153.8	24.8	
Mrk 573	2	4786	0.58	0.14	51.4	7.1	
Mrk 590	1	3077	0.32	0.30	105.9	26.6	NGC 863
Mrk 609	1	3078	0.43	0.25	43.7	16.2	
Mrk 618	1	3077	0.46	0.22	135.6	13.5	
Mrk 704	1	4337	3.58	0.17	61.9	1.4	
Mrk 707	1	5072	0.20	0.24	140.9	52.0	
Mrk 728	1	5073	0.70	0.28	16.0	11.3	
Mrk 734	1	5073	0.35	0.13	95.6	11.0	
Mrk 841	1	4781	0.79	0.12	92.9	4.3	
Mrk 871	1	4780	0.66	0.14	108.0	6.3	
Mrk 896	1	4784	0.55	0.13	1.9	7.1	
Mrk 915	1	4784	0.46	0.15	81.0	9.2	
Mrk 926	1	4785	0.49	0.14	79.5	8.4	
Mrk 938	2	4785	0.56	0.16	168.5	8.0	
Mrk 1239	1	5071	4.09	0.14	136.0	1.0	
NGC 526A	2	4786	0.26	0.20	168.4	22.1	
NGC 985	1	3077	0.82	0.19	98.4	6.5	
NGC 1068	2	2395	2.11	0.02	98.4	0.3	5", C500 filter
NGC 1275	2	2782	3.49	0.10	151.0	0.8	

TABLE 1—Continued

Object	Type	JD + 2,400,000	p (%)	σ_p (%)	θ	σ_θ	Remarks
NGC 1386	2	4334	0.62	0.15	34.3	7.1	
NGC 1566	1	4350	0.60	0.24	52.6	11.6	
NGC 2110	2	4336	0.18	0.21	110.0	52.0	
NGC 2992	2	4338	3.32	0.18	33.3	1.6	
NGC 3080	1	5073	0.45	0.20	159.6	12.6	Mrk 1243
NGC 3081	2	4338	1.43	0.18	84.2	3.6	
NGC 3227	2	2783	1.77	0.09	126.3	1.5	
NGC 3516	1	2923	0.83	0.08	179.0	2.7	
		3544	0.72	0.10	172.0	3.8	4'6
NGC 3783	1	2923	0.44	0.19	110.4	12.1	
		4337	0.49	0.15	114.4	8.6	
NGC 4051	1	2782	0.67	0.10	78.0	4.0	
		2923	0.52	0.09	75.8	4.6	
NGC 4151	1	2921	0.26	0.08	62.8	8.4	
		3222	0.66	0.04	87.5	1.7	5'6
NGC 4235	1	4338	0.11	0.22	127.7	52.0	
NGC 4507	2	4780	0.36	0.14	37.3	10.8	
NGC 4593	1	4338	0.52	0.16	39.6	9.0	
NGC 5506	2	4780	3.10	0.16	84.3	1.5	
NGC 5548	1	2923	0.72	0.10	33.5	3.9	
NGC 5940	1	4781	0.30	0.15	102.7	13.9	
NGC 6814	1	2921	1.77	0.16	175.5	2.7	
		3077	3.07	1.24	19.6	11.6	
NGC 7213	1	4782	0.39	0.08	137.3	5.7	
NGC 7450	2	4785	0.43	0.18	170.1	12.3	Mrk 1126
NGC 7469	1	2785	0.32	0.12	98.7	10.6	
		3077	0.25	0.12	80.6	13.9	
NGC 7582	2	4784	1.03	0.12	172.1	3.4	
NGC 7603	1	2785	0.32	0.29	127.0	27.0	Mrk 530
		3079	0.59	0.23	127.7	11.3	
NGC 7674	2	4786	1.88	0.14	39.2	2.2	Mrk 533
IC 4329A	1	2785	5.74	0.23	44.1	1.1	
IC 4870	2	4780	0.32	0.20	25.2	18.2	
IC 5063	2	4784	1.28	0.14	10.1	3.2	
I Zw 1	1	2783	0.58	0.10	34.2	5.1	
		3079	0.67	0.16	29.7	6.7	
II Zw 1	1	3078	0.39	0.38	131.3	27.8	
II Zw 136	1	3077	0.23	0.20	79.8	25.7	
III Zw 2	1	3080	0.51	0.22	108.7	12.2	
3C 120	1	2784	0.92	0.25	103.5	7.9	II Zw 14
		3079	1.19	0.23	98.8	5.5	
3C 390.3	1	3077	0.84	0.30	161.3	10.3	
		3280	1.98	0.30	149.7	4.4	7'4
Akn 120	1	4334	0.65	0.13	78.6	5.7	Mrk 1095
Akn 202	1	4337	0.49	0.18	130.0	10.4	Mrk 705
ESO 012G21	1	4786	0.75	0.15	106.1	5.6	
ESO 103G35	1	4783	0.43	0.14	20.2	9.5	
ESO 103G56	1	4784	0.89	0.15	155.5	4.9	F182
ESO 113IG45	1	4783	0.40	0.11	2.4	7.6	F9
ESO 140G43	1	4344	5.47	0.19	139.9	1.0	F51
ESO 141G55	1	4344	1.22	0.16	4.4	3.7	
		4782	1.61	0.10	175.0	1.8	
ESO 185IG13	2	4344	1.50	0.30	5.5	5.8	
MCG - 5-23-16	2	4782	0.17	0.15	67.5	24.4	
MCG - 6-30-15	1	4780	4.65	0.13	116.7	0.8	
MCG 8-11-11	1	4556	0.69	0.46	166.4	19.0	UGC 3374
TOL 1351-375	1	4786	4.11	0.18	165.0	1.3	
3A 0557-383	1	5072	4.63	0.17	116.9	1.0	

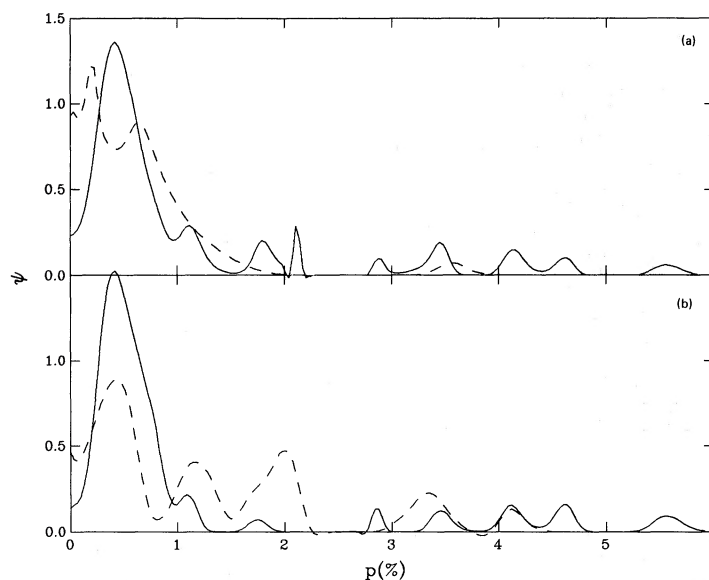


FIG. 1.—The normalized frequency distributions of polarization: (a) for 99 Seyfert galaxies (solid curve) and for 107 QSOs with $p < 6\%$ (dashed curve). (b) for 67 Seyfert 1 galaxies (solid curve) and for 32 Seyfert 2 galaxies (dashed curve).

a) Comparison of the Seyfert Galaxy and QSO Distributions

Although Stockman (1978) has done a similar study for 102 QSOs, to provide a consistent comparison with Seyferts we have repeated the above analysis for 107 QSOs with $p < 6\%$ including new data from Stockman, Angel, and Miley (1979). The result is shown in Figure 1a (there are also three QSOs with $p > 6\%$ not shown). The distributions for Seyfert galaxies and bright QSOs are qualitatively similar: there are many objects with low polarization ($p < 1.5\%$) and few with $p > 2.5\%$, and in neither case does the frequency distribution for large p appear to be a smooth extension of that for low p . Quantitatively the fractions of highly polarized objects (14 out of 99 for Seyfert galaxies, 6 out of 110 for QSOs) do not appear to be significantly different. However, this agreement is undoubtedly fortuitous, since the polarization mechanisms are known to be different. The highly polarized QSOs are optically violent variables in which we are seeing nonthermal polarization of the central source of radiation, as in BL Lac objects. On the other hand, scattering by dust has been shown to cause high polarization in many Seyfert galaxies (see the summary by Thompson *et al.* 1983).

One obvious difference in the distributions is the dip in probability at $p = 0$ for Seyfert galaxies. This is probably not a real difference; it could result from a major qualitative difference between the two surveys: the observational errors in the Seyfert survey are typically half those in the QSO survey. To test this possibility, we artificially doubled the errors in our data and subjected them to the same deconvolution. As expected,

the dip at $p = 0$ was filled in at the expense of a decrease in the peak near $p \sim 0.5\%$. (We note that if the errors in the survey had been very small, then the deconvolution would recover the histogram of the original data, subject to some smoothing.) It therefore appears that had the Seyfert survey been carried out with the lower precision of the QSO survey, the frequency distributions at low polarization would be very similar. (The converse, involving an increase in the accuracy of the QSO measurements, is not necessarily true.) Note, however, that QSOs are relatively more populous in the range above $\sim 0.6\%$; this is not an artifact of the different measuring accuracy.

If it were concluded that the two distributions were similar, then one simple explanation would be the following: most QSOs and Seyfert galaxies are intrinsically unpolarized, and the low amounts of measured polarization are actually caused by a common agent, the foreground interstellar dust in our Galaxy. This possibility is explored for Seyfert galaxies in § IVc and for QSOs in § IVd. It is found that the apparent excess of QSOs relative to Seyferts near $p \sim 1\%$ is probably the result of residual intrinsic polarization in QSOs. However, further details of differences in the distributions after accounting for foreground polarization would be hard to establish. In any case, if there is intrinsic polarization in QSOs and in Seyfert nuclei, the frequency distributions obtained in this manner are still not directly comparable. This arises from the effect of dilution of the nuclear polarization by unpolarized stellar light, as discussed in § III. Because of dilution the Seyfert survey underestimates any intrinsic nuclear polarization. Such effects are, however, miniscule for QSOs.

b) *Comparison of the Seyfert 1 and Seyfert 2 Distributions*

The frequency distributions for 67 Seyfert 1 galaxies and 32 Seyfert 2 galaxies are given in Figure 1b. Here again the distributions are qualitatively similar. The proportions of highly polarized ($p > 2.5\%$) galaxies are similar (10 out of 67 Seyfert 1 galaxies, 4 out of 32 Seyfert 2 galaxies). The typical values of low polarization ($p \sim 0.5\%$) are also the same, as would be expected if foreground interstellar polarization is a substantial common contributor (§ IVc). Thus the presence or absence of polarization is not related to the physical processes which ultimately determine the spectroscopic type 1 or type 2 classification; also, the various mechanisms which can produce high polarization might occur in either type (Thompson *et al.* 1983).

c) *The Contribution of Foreground Interstellar Polarization*

The best way to assess the effects for individual galaxies would be to obtain measurements of adjacent distant field stars or neighboring galaxies and perform a formal subtraction of Stokes parameters. Existing stellar data are unfortunately too sparse to be of use, given the known patchiness of interstellar polarization. We have not acquired the appropriate data during our survey because of the necessarily increased demands on telescope time. Thus we adopt a statistical approach which should be useful at least for interpreting the foregoing frequency distributions. This is a well-defined procedure, but unfortunately it is subject to ill-defined input data whose limitations will be noted below.

The first step of the procedure is recognition that in our Galaxy the degree of polarization p is loosely correlated with E_{B-V} (no use is made of information on θ). Specifically, the data of Serkowski, Mathewson, and Ford (1975, Fig. 6) show that $p_{\max} \approx r9E_{B-V}\% \text{mag}^{-1}$, with r quite uniformly distributed in the range $\frac{1}{3}$ to 1; most of the stars observed have $|b| < 10^\circ$. The color correction from p_{\max} at $\lambda_{\max} \sim 0.55 \mu\text{m}$ to our C4-96 filter is a reduction by a factor ~ 0.95 . The main deficiency in this step is the lack of a large volume of stellar polarization data at high $|b|$ to confirm whether this relationship is still appropriate.

The second step of the procedure makes use of the fact that E_{B-V} follows some type of "cosecant" law with Galactic latitude. We are interested mostly in $|b| > 20^\circ$. One such relation is summarized by Holmberg (1974), $E_{B-V} \approx E_0 \csc|b|$ with $E_0 = 0.054$. The main deficiencies in this procedure are as follows. There is dispute about the value of E_0 , which might be lower by at least a factor 2 (Sandage 1973; Heiles 1976). Values of E_{B-V} calculated by D. Burstein (private communication) from H I data and galaxy counts for the positions of many of our galaxies were about half as large as predicted by this

cosecant law. We ignore the possibility of unusually low reddening and polarization near the Galactic polar caps (e.g., Sandage 1973; Holmberg 1974; Martin 1978). We also neglect the real and considerable scatter, arising from patchiness in the medium, which exists about any proposed law; inclusion of this would broaden the simulated frequency distribution.

This procedure was used to construct an artificial data set corresponding to the 78 galaxies in Table 1 with $p < 1.5\%$. The galactic latitude of each galaxy was used to generate five values (p_0) per galaxy, using r spanning the range $[\frac{1}{3}, 1]$. Each of these values of p_0 was then adjusted to $p_i = (p_0^2 + \sigma^2)^{1/2}$, using the survey value of σ for each galaxy, to simulate what would most likely have been observed when the measuring error is σ . The assembled (p_i, σ) data were then subjected to the deconvolution procedure to find the apparent frequency distribution. The actual data for the same 78 galaxies were also analyzed. Figure 2 displays the results, which are remarkably identical both in peak value and in dispersion. An alternative approach, choosing r randomly within $[\frac{1}{3}, 1]$, was also used. This produced less smooth distributions; the curve shown is a good average of these individual distributions. These simulations suggest that the bump observed at $p \sim 1.1\%$ is probably just the result of a statistical fluctuation.

The above-mentioned deficiencies in the input for the simulation should be sufficient caution against over-interpretation. However, it is encouraging that the simulation does not predict too much polarization. Our opinion is that the polarization is also probably not overestimated by more than a factor 2. Thus we conclude that half, if not all, of the polarization of low-polarization Seyferts in the survey is produced by foreground dust in the Galaxy.

Because of the statistical nature of this simulation and the real clumpiness in the interstellar medium, this approach has limited use for individual galaxies. One might, for example, expect some of the Seyfert galaxies with $p < 1.5\%$ to reveal intrinsic polarization, and this is indeed the case (e.g., NGC 4151, NGC 5548, Mrk 509; see Thompson *et al.* 1983). Conversely, it is important to check for an interstellar contribution for galaxies with $p > 1.5\%$. Among the objects surveyed, only in the case of NGC 6814 do the degree of polarization and position angle agree well with interstellar values in the same direction.

d) *Foreground Polarization in the QSO Sample*

In an earlier study of 44 QSOs Stockman and Angel (1978) concluded that the polarization distribution for $p < 2\%$ could not be explained simply by foreground Galactic contamination, though the latter was not insignificant. We have repeated the analysis of § IVc for a larger sample of 102 QSOs with $p < 2\%$. The result shown in Figure 3 provides a consistent comparison

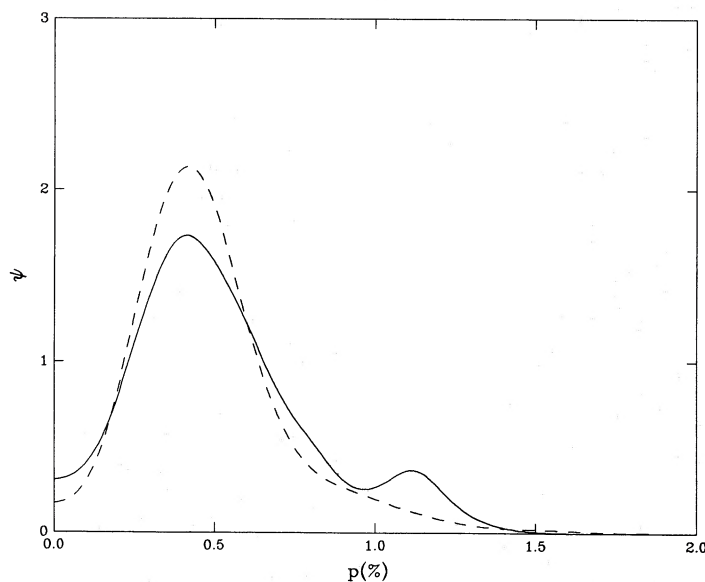


FIG. 2.—Frequency distribution of polarization for 70 Seyfert galaxies with $p < 1.5\%$ (solid curve) and a simulation of the polarization distribution that might be produced by foreground interstellar polarization in the Galaxy (dashed curve).

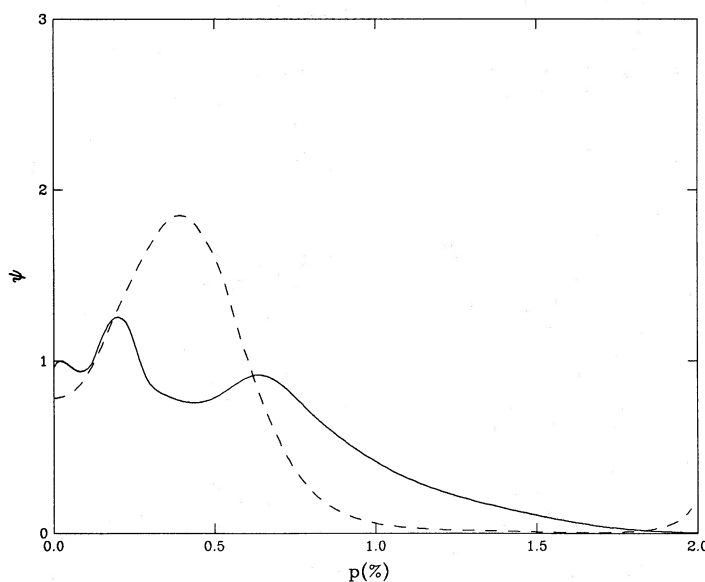


FIG. 3.—As in Fig. 2 but for 102 QSOs with $p < 2\%$

with the result for Seyfert galaxies in Figure 2. There are two points of note. First, the simulation for QSOs suggests a somewhat lower contamination because the typical Galactic latitude for the QSO survey is higher. More important, there is a significant excess in observed QSOs relative to the simulation for $p > 0.6\%$, much more than could be claimed for Seyfert galaxies. When

it is remembered that our simulation probably indicates an upper limit to the contamination, the conclusion that there is residual intrinsic polarization, $p \sim 0.6\% - 1\%$, in many (more than $\sim 1/2$) QSOs seems inescapable. This conclusion is strengthened by the alignment of polarization vectors and radio structure found by Stockman, Angel, and Miley (1979); see § Vb.

V. CLUES TO THE ORIGIN OF OPTICAL POLARIZATION

Detailed continuum and H α polarization observations show that in cases where $p > 1.5\%$ the polarization is often caused by dust, either by scattering in asymmetrically distributed dust clouds (e.g., Mrk 231, Thompson *et al.* 1980) or sometimes by transmission through aligned grains (e.g., IC 4329A, Martin *et al.* 1982). A nonthermal origin has been demonstrated for the unusual variable nucleus in NGC 1275 (Martin, Angel, and Maza 1976) and also for a few well studied cases for which $p < 1\%$ (e.g., NGC 4151, Schmidt and Miller 1980, Thompson *et al.* 1979; Mrk 509, Thompson *et al.* 1983). As shown in § IVc, for those objects with $p < 1\%$ a large fraction of the observed polarization is probably interstellar in origin, but because of the clumpiness of the interstellar medium little more can be said about the degree of intrinsic polarization in individual objects. Statistical evidence for low amounts of intrinsic polarization might be found in correlations with other observables.

Such an approach was followed by Maza (1979) for a sample of 47 Seyfert galaxies. He found that neither the observed polarization nor the polarization corrected for aperture size and, statistically, for foreground polarization was clearly related to the UBV colors, the Balmer decrement, the infrared spectral index, the radio or X-ray luminosity, the Fe emission line strength, or the galaxy morphology. Because of the lack of success of this preliminary study we have not extended it to our larger sample. However, we have determined that for objects with $p < 1\%$ there is no correlation between the observed polarization and either the measured axial ratio of the galaxy (Keel 1980) or the $B - V$ color. These correlations might have been expected if, for example, interstellar polarization in the host galaxy produced the observed polarization of the Seyfert nucleus.

a) Variability

We have repeat observations for 17 polarized galaxies. Of these, only Mrk 3, Mrk 509, NGC 4151, and 3C 390.3 show excursions greater than 2.5σ in the measured polarization (see Table 1). The possibility of variability of Mrk 3 is puzzling because the polarization is known to arise from dust scattering (Thompson *et al.* 1980). It is possible that the low value measured was caused by poor seeing which could introduce significant dilution by unpolarized starlight; this is supported by a drop in the counting rate by a factor 1.6 during this measurement. If the variability of Mrk 3 is intrinsic, then one would have to appeal to mass motions of the scattering material in the nucleus.

Continuum and H α observations of Mrk 509 show that the polarization in this galaxy is most likely nonthermal in origin (Thompson *et al.* 1983) and the varia-

bility is similar to that seen in NGC 4151. The variability of NGC 4151 has been discussed previously (Thompson *et al.* 1979; Kruszewski 1977), as has that of 3C 390.3 (Angel and Stockman 1980). Rapid variability in the nonthermal source NGC 1275 is discussed by Martin, Angel, and Maza (1976) and Maza (1979). Maza (1979) also examined the historical record for several other galaxies but found no further convincing candidates for variability.

b) Alignment with Radio Structure

For a sample of 24 QSOs Stockman, Angel, and Miley (1979) found that the position angle of the polarization correlated well with the position angle of the spatial structure of radio emission. We have verified that there are two reasons why this result was not obscured by the effects of foreground Galactic optical polarization. First, this sample has on the average higher Galactic latitude than all 110 QSOs. More importantly, there is a strong selection effect: optical position angles must be known to better than 15° . In a sample with comparable measurement errors in degree of polarization this criterion tends to select QSOs with higher polarization, and thus those with significant intrinsic polarization. These are among the QSOs which produce the tail in the frequency distribution above $p \sim 0.6\%$ where foreground contamination is least significant (see Fig. 3).

Position angles of linear radio sources, with double, triple, or jetlike structure, are available for 11 Seyfert galaxies (Wilson *et al.* 1980; Ulvestad, Wilson, and Stamek 1981; Wilson 1982; Wilson, private communication). For nine of these the position angle of the optical polarization is known to an accuracy of better than 15° . In contrast to the case of QSOs, no correlation with the polarization position angle is seen. This is consistent with optical polarization being largely Galactic foreground. If the observed polarization is intrinsic to these Seyfert galaxies, then the mechanism does not give rise to the striking alignment seen for QSOs; this might suggest a different mechanism.

VI. NARROW EMISSION LINE GALAXIES

In the course of this survey we have also observed a number of galaxies which were initially identified as Seyfert galaxies in the literature but which were shown later to be narrow emission line galaxies. The observations of these are presented in Table 2. Two of these galaxies show detectable polarization, but our sample of these objects is too small to compare their polarization properties with those of the Seyfert sample.

The position angle of the polarization of NGC 6951 is not consistent with that of stars close to it on the sky (as

TABLE 2
LINEAR POLARIZATION OBSERVATIONS OF NARROW
EMISSION LINE GALAXIES

Object	JD +2,440,000	p (%)	σ_p (%)	θ	σ_θ
Mrk 391	2782	0.41	0.22	34.4	15.2
Mrk 471	2923	0.46	0.33	72.4	27.2
Mrk 577	3078	0.63	0.35	156.5	15.8
Mrk 789	4782	0.66	0.15	155.2	6.3
NGC 1614 ...	2782	1.29	0.20	160.8	4.5
	3079	2.11	0.30	157.2	4.1
NGC 3998 ...	2922	0.25	0.14	35.1	16.0
NGC 6764 ...	3077	0.17	0.24	116.6	52.0
NGC 6951 ...	2921	2.62	0.25	116.1	2.7
	3080	2.72	0.29	116.8	3.0
	3080 ^a	1.77	0.26	118.1	4.2

$$^a \lambda^{-1} = 1.2 \mu\text{m}^{-1}, \Delta\lambda^{-1} = 0.1 \mu\text{m}^{-1}.$$

tabulated in interstellar polarization catalogs), suggesting that some of the observed polarization may be intrinsic. This could be verified by measuring the ultraviolet polarization. Since it is unlikely that there is much of a nonthermal component in the optical continuum of NGC 6951, any intrinsic polarization is probably produced by dust scattering or transmission. A more extensive polarization survey of narrow emission line galaxies is obviously of interest.

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