Ann. Rev. Astron. Astrophys. 1980. 8 : 321–61

OPTICAL AND INFRARED POLARIZATION OF ACTIVE EXTRAGALACTIC OBJECTS

×2169

J. R. P. Angel and H. S. Stockman
Steward Observatory, University of Arizona,
Tucson, Arizona 85721

I *Introduction*

In bringing together the material for this review our attention was drawn repeatedly to the remarkably similar characteristics of virtually all strongly polarized extragalactic objects, which are found as the nuclei of giant elliptical galaxies or as quasi-stellar sources. These are violent variability, a compact, flat-spectrum radio source, and a very smooth continuum extending at least to 10 μ. These properties are common to the polarized sources in BL Lac objects over a wide range of luminosity and to some QSOs and radio galaxies. In view of the similarities, which suggest a common process of energy release close to the central core of these objects, we will treat them all as a single group. In a memorable banquet speech at the Pittsburgh meeting on BL Lac objects (the only words spoken not faithfully reported in the proceedings) Ed Spiegel suggested the name "blazar" for this class of object. A combination of BL Lac object and quasar, with a strong feeling of the characteristic violent optical flaring, blazar seems an excellent name, one which we will adopt throughout the review. As we shall discuss in Sections V and VI, blazars may not be a different type of object from most quasars or active elliptical galaxies. These normal objects may have jets whose emission is beamed by relativistic bulk motion, and show blazar characteristics only when pointed at us. In reviewing the observational data we will be especially conscious of properties that could help distinguish an isotropic source from a beamed one.

The blazars form only a small portion of active extragalactic objects. Optical emission from most QSOs and Seyfert nuclei shows only very small

0066-4146/80/0915-0321$01.00

polarization and little optical variability, and is perhaps the result of thermal or scattering processes. For these objects we will try to assess the information about source geometry and emission that can be derived from polarization data, particularly from the spectrum of polarization.

Polarization of active extragalactic objects has not been comprehensively reviewed in the past except by Visvanathan (1974) and Hagen-Thorn (1974). Both authors include rather complete discussions of the polarization by scattering in normal galaxies and the dusty halo of M82. In the interest of brevity we will not discuss these types of extended objects, except to point the reader to recent discussions of M82 by Bingham et al. (1976) and by Schmidt, Angel & Cromwell (1976). In this review we consider first the compact extragalactic sources for which strong polarization has been measured. The number of these is small enough, about 60, that we are able to at least mention them all. In Section II we first list the blazars, which form the large majority of the strongly polarized objects, and summaries of the observational data of some individual objects are given. The optical-infrared polarimetric properties and correlations of polarization with other properties of blazars are discussed in Section III. The remaining compact objects that show high polarization are PHL 5200 and knots in the jet of M87, whose properties are reviewed in Section II, and several Seyfert nuclei. The polarization properties of Seyfert nuclei, nearly all of which seem to be polarized by dust, and the majority of QSOs, which have only weak polarizations of unknown origin, are reviewed in Section IV. Theoretical models for the origin of optical-infrared polarization are reviewed in Section V, while in Section VI we consider how the observations of polarization can be accommodated by relativistically beamed jets. We finish in Section VII with some directions for future work.

II *Strongly Polarized Objects*

In this section, we summarize the optical-infrared and radio observations for all extragalactic objects that appear to be blazars and for which strong polarization has been measured, $\gtrsim 3\%$. We believe that the study of line-free, BL Lac objects has suffered from being too removed from the study of other polarized active objects. To redress that imbalance, the objects appearing in Table 1 have been included without regard to intrinsic luminosity or the presence of emission lines. A few faint objects, for which only single measurements of poor accuracy are available, have been omitted. Following Table 1, we present individual summaries of those interesting objects that bridge the compartments or subclasses of BL Lacs, QSOs, radio galaxies, etc. M87 and PHL 5200, which are strongly polarized but do not fall into the blazar class, are also summarized. A discussion of the only other compact extragalactic objects known, the strongly polarized Seyfert nuclei, is deferred until Section IV.

The information on blazars summarized in Table 1 is as follows. Coordinate designation and names are given in the first two columns, the redshifts where known and their sources are given in columns 3 and 4. If no emission lines are detected, and the redshift is that of the host galaxy, a "g" superscript is given. If absorption lines in the continuous spectrum are the only indication of distance, z is given as greater than that of the absorption lines. Rough visual magnitudes and their sources are given in columns 5 and 6. In the next three columns we summarize the optical polarization values with the appropriate reference(s) in column 10. Column 9 gives the number of separate measurements. The ranges of percentage polarization and position angle of the electric vector appear in columns 7 and 8. In column 11, we note whether the sources are known to have strong (s), weak (w), or no detectable emission lines (no entry). References to spectra are in column 12. The optical spectral index, α (column 13), and the known range of B magnitude (in magnitudes, column 15) are derived from the references in columns 14 and 16 respectively. In the next eight columns (17–24), we list radio flux measurements at frequencies of 178 MHz, 408 MHz, 1.4 GHz, 2.7 GHz, 5 GHz, 8.08 GHz, 22.2 GHz, and 90 GHz. This may seem rather clumsy, but there is no simple parameter that can describe the spectrum shape over nearly three decades in frequency. References to the radio spectra are given in column 25, and to additional data in column 26.

In the following discussion of individual objects and throughout this paper we will assume that the redshifts are cosmological with $H_0 = 75$ km s^{-1} Mpc^{-1}, and adopt $q_0 = 1/2$ when needed for objects at high z. The spectral index α will be defined by $F_\nu \alpha \nu^{-\alpha}$ for both optical and radio spectra.

0316+413 = NGC 1275 = 3C 84 This source is of special interest in being the closest listed in Table 1, at $z = 0.016$. It is the nucleus of the dominant central galaxy of the Perseus cluster, and is distinguished by the presence of moderate strength emission lines (Table 2) and a radio halo of steep spectrum around the compact flat-spectrum core.

Optical polarization of the nucleus was first reported by Dibaj & Shakhovskoy (1966), and it has since been repeatedly measured by Walker (1968) and by Babadzhanyants, Hagen-Thorn & Dombrovsky (references in Babadzhanyants & Hagen-Thorn 1975). This work showed the polarization to vary from month to month in strength up to 3% ($26''$ aperture), while nearly all points lie between 100° and 150° in position angle. More recently Martin, Angel & Maza (1976) and Angel et al. (1978) found erratic changes in position angle of up to 20° from night to night. Through a small aperture ($4''$) centered on the nucleus the polarization can be as strong as 6%

Table 1 Strongly polarized compact extragalactic objects

						Optical polarization				Emission lines			
(1)	Object (2)	z (3)	Ref.[b] (4)	V (5)	Ref.[b] (6)	P (7)	θ (8)	N (9)	Ref.[b] (10)	(11)	Ref.[b] (12)	α (13)	Ref.[b] (14)
0048−097	OB-081	—	*128*	16	*105*	7–14	—	3	*53, 143*		*15*	1.8	*112*
0109+224	GC	—	*128*	15.5	*128*	3–6	55–85	2	*0, 90*		*85*		
0215+015	PKS	≧1.345	*37*	18.3	*128*	20	—	1	*37*		*37*	1.9	*37*
0219+428	3C 66A	.444?	*69*	15.5	*128*	6–15	170–45[p]	41	*2, 53, 142*	w	*69*	1.1[v]	*69, 112*
0235+164	AO	≧.852	*93*	16.0	*128*	6–25	15–175	10	*0, 2, 66, 93*		*93*	4.0	*93*
0300+470	4C 47.08	—	*128*	18.0	*128*	12–24	70–85	2	*0, 90*		*132*		
0316+413	NGC 1275	.0172	*102*	11.9	*102*	1–6	100–160[p]	50	*discussion*	s	*126*		
0403−132	PKS	.571	*13*	17.2	*13*	0–4	170–195	6	*0, 106*	s		1.1	*13*
0420−014	PKS	.915	*13*	18.0	*13*	8–20	150–175	7	*0, 68*	s			
0422+004	OF 038	—	*128*	16.0	*128*	6–22	140–210[p]	36	*2*		*132*		
0521−365	PKS	.055	*128*	15.0	*128*	6	155	1	*0*	w	*28*	1.0[v]	*28, 53*
0548−322	PKS	.069[g]	*105*	15.5	*105*	1.5–2	0–15	2	*0*			1.8	*53*
0735+178	PKS	≧.424	*13*	15.5	*13*	3–31	0–175	90	*2, 16, 53, 74 90, 94*		*69*	1.3[v]	*53, 69 112*
0736+017	PKS	.191	*13*	16.5	*13*	.5–6	25–135	9	*0, 106, 118*	s		1.1	*6*
0752+258	OI 287	.446	*13*	17.0	*13*	8	145[p]	8	*0, 106*	s			
0754+100	OI 090.4	—	*128*	14.5	*128*	3–26	0–140	65	*2, 27, 90, 94, 113*		*113*		
0808+019	OJ 014	—	*128*	17.5	*128*	4–14	—	5	*53*			0.9	*53*
0818−128	OJ-131	—	*128*	15.5	*128*	8–36	60–115[p]	45	*2, 27, 113*		*113*		
0829+046	OJ 049	—	*128*	16.5	*128*	12	110–115	2	*0*		*100*	2.3	*53*
0851+202	OJ 287	.306?	*69*	14.0	*128*	1–32	0–180[p]	220	*2, 30, 42, 49, 53, 54, 73, 90, 108, 121, 130*	w	*69*	1.4	*53, 69*
0906+430	3CR 216	.670	*13*	18.5	*13*	3–21	—	3	*53, 0*	s	*104*	1.8	*53, 104*
0912+297	OK 222	—	*128*	16.0	*128*	4–13	—	10	*53*		*132*	1.3	*53, 112*
0957+227	4C 22.25	—	*128*	18.0	*128*	2–4[a]	—	2	*53*		*95*	.9	*53*
1057+100	HM	—	*128*	17.5	*128*	1–10	—	7	*53, 143*		*109*	1.3	*112*
1101+384	Mkn 421	.030[g]	*69*	13.5	*128*	0–7	150–185[p]	25	*53, 65, 66, 90, 94, 114*		*69*	1.1	*69*
1133+704	Mkn 180	.044[g]	*69*	15.0	*128*	1–4	120–145	3	*0*		*69*		
1147+245	OM 280	—	*128*	16.0	*128*	3–13	5–155[p]	17	*2, 53, 143*		*109*	1.9[v]	*112*
1150+497	4C 49.22	.334	*13*	16.1	*13*	0–4[a]	20–180	7	*0, 106*	s			
1156+295	4C 29.45	.729	*13*	15.6	*13*	1–9	0–120	6	*0, 106*	s		.93	*91*
1215+303	ON 325	—	*128*	15.5	*128*	4–17	120–180[p]	62	*2, 53, 74, 108*			1.8	*112*

Table 1–*continued*

(1)	Object (2)	Δm (15)	Ref.[b] (16)	0.18 (17)	0.41 (18)	1.40 (19)	2.70 (20)	5.00 (21)	8.08 (22)	22.2 (23)	90.0 (24)	Ref.[b] (25)	Comments[b] (26)
				Radio spectrum fluxes in Jy at frequencies given in GHz									
0048−097	OB-081	2.7	*116*		0.6	1.1	1.4[v]	2.0[v]	2.4[v]		2.0[z]	*1,32,36,47,124*	VLBI (*45*)
0109+224	GC	3.1	*85*	<2	0.4[u]	0.7	1.9	1.2[v]	0.5[w]	0.5	0.8[v]	*23,80,81,86,100*	
0215+015	PKS	3.5	*37*	<2	0.8[u]	0.5	0.4	0.4	<1.2			*9,23,39,83,*	
												122,123	
0219+428	3C 66A	1.0	*105*		5.0	1.3					<0.2	*61,81*	
0235+164	AO	5.2	*87,93*	<2	1.5	2.6	1.5[v]	2.8	2[v]	2.3	2.2	*1,39,81,83,110*	
0300+470	4C 47.08			2.2		2.1	2.3[v]	2.2	2.8[v]	3.3	2.2	*1,11,39,81*	Compact radio (*88*)
0316+413	NGC 1275			63	29	13	16[v]	30[v]	50[v]	36[v]	36[v]	*1,39,44,61,81*	Core-halo radio (*10, 46*)
												127,133,141	X-ray source
0403−132	PKS	.8	*40*	7.8[t]	7.2	3.2	2.9	2.8[v]				*32,36,97,101,124*	Compact radio (*24*)
0420−014	PKS	2.8	*87*	1.8	1.2	1.5[v]	1.6[v]	1.8[v]	2.1[v]	3.3	4.1	*9,32,81,82,123*	VLBI (*24,45,46*)
0422+004	OF 038	1.5	*135*	1.5	1.2[u]	1.3[v]	1.0[v]	1.2[v]	1.0[v]	1.6	1.7	*9,22,36,81,*	
												83,123	
0521−365	PKS	1.4	*117*	67[t]	26	15	11	10				*32,36,98,101*	Ext. radio (*28*), X-ray (*56, 96*)
0548−322	PKS				<2		0.3					*32,99*	X-ray source (*72, 92, 96*)
0735+178	PKS	2.5	*87*	2.9[t]	2.3[u]	2.2[v]	2.0[v]	2.0	2[v]	2.2	2.0	*1,10,23,32,81,*	VLBI (*43, 45*)
												101	
0736+017	PKS	1.0	*67*	1.1	2.6	2.6[v]	2.2[v]	2.0[v]	2.0[v]	2.6	3.4	*9,32,81,98,123*	VLBI (*24, 45*)
0752+258	OI 287			<2	1.4	0.5						*20,75,86*	Constant polarization (*0*)
0754+100	OI 090.4	1.0	*27*	<2	<2	0.7	0.8	0.9				*32,39,75,100*	
0808+019	OJ 014			<0.5	0.5[u]	0.5	0.7[v]	0.9[v]	<1.2			*9,22,36,98,*	
												122,123	
0818−128	OJ-131	2.9	*27*	3.1[t]	<2	1.1	0.9	0.8				*8,32,75,101*	
0829+046	OJ 049	5.0	*117*	<2	<2	0.6	0.6	0.7	0.7[v]		0.5	*9,32,39,81,100*	
0851+202	OJ 287	4.0	*87*	<2	0.6[u]	1.5	2.8[v]	2.6	5[v]	2.8	7[v]	*1,23,31,82,*	
												86,141	
0906+430	3CR 216			20	12	3.7	2.4	1.8	1.4[w]	1.0[y]		*33,39,44,84,133*	
0912+297	OK 222	1.9	*117*	<2	0.5	0.6						*19,75,86*	
0957+227	4C 22.25			3.7	2.7	1.1	0.7	0.4				*23,82,86,136*	Extended radio (*98*)
1057+100	HM			<2	1.2	0.6						*32,39,136*	
1101+384	Mkn 421	4.6	*105*	<2	1.1	0.6	0.6	0.7	0.5	0.4	0.5	*59,81,86,136*	X-ray source (*72, 96*)
1133+704	Mkn 180			<2			0.2	0.2	0.1	0.4[x]	0.2	*39,59,115*	
1147+245	OM 280			<2	0.8	0.6		1.0		0.8[x]	0.7	*20,75,80,82,86*	
1150+497	4C 49.22	2.0	*106*	5.6	3.2	1.4	1.6	1.1	1.5[w]	0.4[y]		*5,84,86,133*	Extended radio (*24*)
1156+295	4C 29.45	2.6	*0*	2.8	2.8	1.7		0.9				*19,75,82,86*	Compact radio (*24*)
1215+303	ON 325	2.1	*117*	<2	0.8	0.3		0.4				*19,75,82,86*	

Table 1—*continued*

(1)	Object (2)	z (3)	Ref.[b] (4)	V (5)	Ref.[b] (6)	Optical polarization P (7)	θ (8)	N (9)	Ref.[b] (10)	Emission lines (11)	Ref.[b] (12)	α (13)	Ref.[b] (14)
1219+285	W Com	—	*128*	16.5	*128*	2–10	30–95	14	*53, 74, 108*		*108*	2.3	*112*
1253−055	3C 279	.538	*13*	17.7	*13*	4–19	10–180	14	*0, 34, 51, 120*	s		1.6	*76*
1308+326	B2	.996	*69*	19.0	*128*	0–25	25–160	44	*70, 89, 90*	s	*69*	1.6	*69, 89*
1400+162	MC 3	.244	*7*	16.5	*13*	4–14	80–100[p]	6	*0, 7, 74*	w	*7, 69*	1.5[v]	*7, 69*
1418+546	OQ 530	—	*128*	15.0	*128*	2–19	50–105	5	*27, 90*		*27*		
1514+197	GC	—	*128*	18.5	*128*	7–9	—	2	*53*			2.3	*53*
1514−241	AP Lib	.049	*69*	15.0	*128*	2–7	145–205[p]	18	*2, 14, 53, 108*	w	*69*	2.7	*53*
1522+155	MC 3	.628	*13*	17.3	*13*	3–13	10–105	2	*0*	s		.20	*103*
1538+149	4C 14.60	—	*128*	15.5	*128*	22	—	1	*53*		*131, 132*	1.9[v]	*112*
1641+399	3CR 345	.595	*13*	16.0	*13*	2–16	10–170	49	*0, 3, 34, 51, 52, 55, 58, 107, 120*	s		1.1	*76, 120*
1652+398	Mkn 501	.034[g]	*69*	13.8	*105*	2–4	125–145[p]	36	*2, 53, 65, 90, 114*		*69*	2.5	*112*
1717+178	OT 129	—	*128*	18.5	*128*	27	—	1	*27*		*132*		
1727+502	I Zw 186	.055[g]	*69*	16.0	*128*	4–6	—	6	*53*		*69*	1.9[v]	*112*
1749+096	OT 081	—	*128*	17.0	*105*	3–9	—	3	*53*		*109*	2.2[v]	*112*
1807+698	3CR 371	.050	*102*	14.8	*102*	0–12	65–100[p]	68	*0, 14, 53*	w	*69*	1.3	*69*
1845+797	3CR 390.3	.056	*102*	14.5	*102*	1–4	155–165[p]	30	*0, 4*	s	*79*		
2032+107	MC	—	*128*	18.6	*128*	12	130	1	*134*				
2155−304		.17?	*17*	14.0	*128*	3–7	150–170	4	*41*	w	*17*	1.0	*41*
2200+420	BL Lac	.069	*69*	14.5	*105*	2–23	0–180	>500	*0, 2, 53, 57, 74, 90, 119, 120*	w	*69*	1.6[v]	*69, 105*
2201+171	MC 3	1.080	*13*	18.8	*13*	9.5	30	1	*134*				
2208−137	PKS	.392?	*13*	17.0	*13*	5–9	100–170	3	*0*	s			
2223−052	3C 446	1.404	*13*	18.4	*13*	4–17	10–160	16	*0, 50, 68, 107, 120*	s		1.8	*76, 120*
2225−055	PHL 5200	1.981	*13*	17.7	*13*	4	160[p]	3	*0, 107*	s			
2230+114	CTA 102	1.037	*13*	17.3	*13*	1–11	100–170	6	*0*	s		1.0	*76*
2251+158	3CR 454.3	.859	*13*	16.1	*13*	0–16	0–170	24	*0, 107, 118, 120*	s		1.5	*76, 120*
2254+074	OY 091	—	*128*	16.5	*128*	14–21	—	6	*53, 143*		*109, 132*	2.1[v]	*112*
2345−167	PKS	.600	*13*	18.0	*13*	3–19	70–160	3	*0*	s			

Table 1—*continued*

(1)	Object (2)	Δm (15)	Ref.[b] (16)	Radio spectrum fluxes in Jy at frequencies given in GHz 0.18 (17)	0.41 (18)	1.40 (19)	2.70 (20)	5.00 (21)	8.08 (22)	22.2 (23)	90.0 (24)	Ref.[b] (25)	Comments[b] (26)
1219+285	W Com	4.0	*117*	0.8^{u}	0.3	1.4	1.5^{v}	0.7	1.6^{v}	1.2	1.0	*1, 20, 23, 81, 82*	
1253−055	3C 279	6.7	*31*	21	11	10	12	16		9^{y}	6.6^{v}	*32, 39, 47, 97, 141*	VLBI (*26, 45, 46*) X-ray source (*111*) Superluminal (*138*)
1308+326	B2	5.6	*38*	<2	1.2	1.0		1.5	1.8^{w}	3.0	2.7	*19, 81, 83, 86*	
1400+162	MC 3			2.2	1.9	0.8	0.6	0.4		0.3^{x}		*7, 36, 39, 110*	Double radio (*7*)
1418+546	OQ 530	4.8	*27*	<2		0.8	0.9	1.1	1.4^{w}	0.7	0.7	*39, 75, 81, 84*	
1514+197	GC			<2	0.5^{u}		0.5	0.5				*39, 100*	
1514−241	AP Lib	2.5	*37*		3.8	2.1	2.2^{v}	1.9	2.8^{v}			*1, 32, 36*	Core-halo radio (*48*)
1522+155	MC 3			<2	0.6							*39, 110*	
1538+149	4C 14.60	>2.8	*117*	3.6	2.3	2.1	2.0	2.0			0.5	*39, 44, 71, 81, 82*	
1641+399	3CR 345	2.0	*40*	12	9.0	6.6	9.0^{v}	8.0^{v}	9.0^{v}	9.0	7.7^{v}	*1, 21, 44, 81, 84, 86, 141*	D2 (*29*), VLBI (*24, 29, 45, 46, 140*) Superluminal (*138*, 139)
1652+398	Mkn 501			2.0	1.8	1.5	1.4	1.4	1.2	0.9	0.7	*20, 59, 81, 84, 86, 136*	X-ray source (*72, 96*)
1717+178	OT 129			<2	<0.3^{u}	0.5	0.7	0.7^{v}				*23, 39, 75, 100*	
1727+502	I Zw 186	1.9	*117*	<2		0.4		<0.5				*39, 75, 84*	X-ray source (*56*)
1749+096	OT 081			<2	1.3^{u}	1.3	1.0	1.8	1.5			*1, 23, 36, 39, 82*	
1807+698	3CR 371	2.0	*117*	5.3		2.6	1.9	2.0^{v}	1.8^{w}	2.1	1.4	*39, 44, 81, 84*	*N* gal. X-ray source (*96, 63*) Extended radio? (*12, 18, 33, 35*)
1845+797	3CR 390.3	1.8	*117*	47	34	12	6.8	4.5				*44, 60, 102*	*N* gal. Double radio (*60*)
2032+107	MC			<2	1.4	1.2	0.9	0.8				*39, 75, 100, 110*	X-ray source (*63*)
2155−304		1.4	*41*		2	0.3	0.3	0.3				*32, 75, 136*	X-ray source (*41, 96*)
2200+420	BL Lac	4.0	*117*	<2	3.1	5.3^{v}	5.0^{v}	5.5^{v}	7.0^{v}	10^{v}	11^{v}	*1, 10, 39, 46, 47, 81, 84, 133, 136, 141*	VLBI (*46, 48*); X-ray upper limit (*96*)
2201+171	MC 3			<2	1.1	0.8	0.6	0.7				*39, 75, 83, 100, 110*	
2208−137	PKS				<2		0.7	0.5				*8, 32*	
2223−052	3C 446	3.4	*87*	17	8.5	5.8	4.6	4.3		4.8^{y}	3.0	*32, 39, 47, 97*	VLBI (*45, 46*); X-ray source (*111*)
2225−055	PHL 5200	0?	*40*		<0.1		<0.4					*8, 137*	Radio quiet; constant polarization
2230+114	CTA 102	1.0	*0, 40*	5.5	8.0^{v}	6.5^{v}	4.5^{v}	3.5	2.5^{v}	1.3^{y}	0.6	*1, 10, 32, 36, 39, 47, 97, 129*	VLBI (*43, 45, 46*)
2251+158	3CR 454.3	2.3	*117*	13	14	12^{v}	12^{v}	16^{v}	12^{v}	6.9^{v}	5.4^{v}	*1, 32, 36, 39, 47, 97, 98, 141*	D2 (*29*) VLBI (*24, 43, 45, 46, 48*)
2254+074	OY 091	1.6	*117*	<2	0.4^{u}	0.4	0.7	0.8^{v}	1.9^{w}			*23, 39, 75, 83, 100*	
2345−167	PKS	2.5	*87*	2.0^{t}	2.1	2.5^{v}	2.5^{v}	3.6				*32, 36, 101*	VLBI (*45, 46*)

Footnote to Table 1

[a] A general description is given in the text. Table notes are as follows—a: the polarization maximum is uncertain, g: redshift derived from the host galaxy absorption lines, p: polarization has preferred angle, t: flux measurement at 160 MHz, u: 318 MHz, w: 10.7 GHz, x: 15.1 GHz, y: 31.5 GHz, z: 86.0 GHz, v denotes that the radio flux is variable, and a mean value of reported values is given. v against a spectral index indicates that different values are reported in the cited references, and the lower value is given.

We should caution that the radio fluxes in this table are mostly obtained at different occasions at different frequencies, and so the shapes are not reliable for variable sources. Simultaneous observations are given by Owen & Mufson (1977), Owen, Spangler & Cotton (1980), and O'Dell et al. (1978). Jones & Rudnick (1980) find that fractional variations at 90 GHz are probably greater than at lower frequencies. Absence of a v superscript should not be taken as an indication of stability, only that variability is not established from the limited published observations.

[b] References:

0 Steward Obs, unpublished data
1 Altschuler & Wardle 1976
2 Angel et al. 1978
3 Babadzhanyants et al. 1972
4 Babadzhanyants & Hagen-Thorn 1975
5 Bailey & Pooley, 1968
6 Baldwin 1975
7 Baldwin et al. 1977
8 Bolton, Shimmins & Wall 1975
9 Brandie & Bridle 1974
10 Bridle et al. 1972
11 Bridle & Fomalont 1974
12 Broderick et al. 1972
13 Burbidge, Crowne & Smith 1977
14 Capps & Knacke 1978
15 Carswell et al. 1973
16 Carswell et al. 1974
17 Charles, Thorstensen & Bowyer 1979
18 Cohen et al. 1971
19 Colla et al. 1970
20 Colla et al. 1972
21 Colla et al. 1973
22 Condon & Jauncey 1974a
23 Condon & Jauncey 1974b
24 Conway et al. 1974
25 Cooke et al. 1978
26 Cotton et al. 1979
27 Craine, Duerr & Tapia 1978
28 Danziger et al. 1979
29 Davis, Stannard & Conway 1977
30 Dyck et al. 1971
31 Eachus & Liller 1975
32 Ekers 1969
33 Elsmore & Mackay 1969
34 Elvius 1968
35 Fomalont & Moffet 1971
36 Gardner, Whiteoak & Morris 1975
37 Gaskell 1978
38 Gottlieb & Liller 1976
39 Gower, Scott & Wills 1967
40 Grandi & Tifft, 1974
41 Griffiths et al. 1979
42 Hagen-Thorn 1972
43 Jauncey et al. 1970
44 Kellermann et al. 1969
45 Kellermann et al. 1970
46 Kellermann et al. 1971
47 Kellermann & Pauliny-Toth 1971
48 Kellermann et al. 1977
49 Kikuchi et al. 1976
50 Kinman, Lamla & Wirtanen 1966
51 Kinman 1967
52 Kinman et al. 1968
53 Kinman 1976
54 Kinman et al. 1974
55 Kinman 1977
56 Kinzer 1978
57 Knacke, Capps & Johns 1976
58 Knacke, Capps & Johns 1979
59 Kojoian et al. 1976
60 MacDonald, Kenderine & Neville 1968
61 Mackay 1971
62 Mackay 1969
63 Marshall et al. 1978
64 Martin, Angel & Maza 1976
65 Maza, Martin & Angel, 1978
66 Maza 1979
67 McGimsey et al. 1975
68 Miller & French 1978
69 Miller, French & Hawley 1978
70 Moore et al. 1980
71 Munro 1972
72 Mushotzky et al. 1978
73 Nordsieck 1972
74 Nordsieck 1976
75 Ohio 1415 MHz survey
76 Oke, Neugebauer & Becklin 1970
77 Oke 1966
78 Osterbrock & Miller 1975
79 Osterbrock, Koski & Phillips 1976
80 Owen & Mufson 1977
81 Owen et al. 1978
82 Pauliny-Toth & Kellermann 1972
83 Pauliny-Toth et al. 1972
84 Pauliny-Toth et al. 1978
85 Pica 1977
86 Pilkington & Scott 1965
87 Pollock et al. 1979
88 Porcas, Treverton & Wilkinson 1974
89 Puschell et al. 1979
90 Puschell & Stein 1980
91 Richstone & Schmidt 1980
92 Riegler, Agrawal & Mushotzky 1979
93 Rieke et al. 1976
94 Rieke et al. 1977
95 Schmidt 1974

96 Schwartz et al. 1979
97 Shimmins, Manchester & Harris 1969
98 Shimmins & Bolton 1972
99 Shimmins & Bolton 1974
100 Shimmins, Bolton & Wall 1974
101 Slee 1977
102 Smith, Spinrad & Smith 1976
103 Smith et al. 1977
104 Smith 1978
105 Stein, O'Dell & Strittmatter 1976
106 Stockman 1978
107 Stockman & Angel 1978
108 Strittmatter et al. 1972
109 Strittmatter et al. 1974
110 Sutton et al. 1974
111 Tananbaum et al. 1980
112 Tapia, Craine & Johnson 1976
113 Tapia et al. 1977
114 Ulrich et al. 1975
115 Ulrich 1978
116 Usher, Kolpanen & Pollock 1974
117 Usher 1975
118 Visvanathan 1968
119 Visvanathan 1969
120 Visvanathan 1973a
121 Visvanathan 1973b
122 Wall, Shimmins & Merkelijn 1971
123 Wall 1972
124 Wall, Wright & Bolton 1976
125 Wampler 1967
126 Wampler 1971
127 Wardle 1971
128 Weiler & Johnston 1979
129 Williams, Kenderdine & Baldwin 1966
130 Williams et al. 1972
131 Wills & Wills 1974
132 Wills & Wills 1976
133 Witzel et al. 1978
134 Zotov & Tapia, 1979
135 Kinman 1976, *IAU Circ. No. 2908*
136 From *Ohio Master List of Radio Sources*
137 Mills & Little 1970
138 Seilestad et al. 1979
139 Cohen et al. 1979
140 Readhead et al. 1979
141 Hobbs & Dent 1977
142 Puschell 1980
143 Serkowski & Tapia 1975

in the blue (Maza 1979). The position angle during 1976–1978 showed again nearly all points in the range 100°–150°. Interstellar polarization from our own galaxy does not affect the results for NGC 1275 appreciably, the polarization of three nearby galaxies in the cluster being 0.4% at 101°. In addition to the polarization variability, rapid variability of the optical continuum strength also on a time scale of a day, has now been observed (Geller, Turner & Bruno 1979).

The structure of the very bright compact radio core of NGC 1275, which is not polarized, has been explored by VLBI measurements. At centimeter wavelengths the emission is concentrated in three very small components in a line about 3 pc in length, at position angle 170°. The relative motion of the components is not greater than 0.05 pc/yr, or 0.15 c.

PKS 0521 − 36 and 1807 + 698 = 3C 371 These two sources are very similar and are distinguished by their combination of forbidden emission lines and strong, steep-spectrum extended components to their radio emission. Both are strongly polarized variable nuclei located in giant elliptical galaxies at about the same distance ($z \sim 0.05$). In both sources, the narrow forbidden lines of [O III] are about 10 times stronger than in BL Lac (Table 2). PKS 0521 − 36 has been studied most recently in the optical by Danziger et al. (1979). After subtracting the galaxy, they estimate the spectral index in the optical to be ~1.0. No polarization data are reported in the literature, but we recently obtained one measurement through a 4 arcsec aperture, giving $P = 6\%$ at angle 155°. The low-frequency radio emission from 0521 − 36 is strong (67 Jy at 178 MHz), or about the same

Table 2 Absolute luminosity of emission lines in units of 10^{41} ergs s^{-1} in the rest frame of the source, computed using $H_0 = 75$ km s^{-1} Mpc^{-1}, $q_0 = \frac{1}{2}$

	Object	MgII 2798	[OII] 3727	Hβ 4861	[OIII] 5007	Hα 6563	Ref.
0316+413	NGC 1275	—	1.5	0.8	3.0	8	Wampler 1971
0521−365	PKS	—	3	—	1.0	1.1	Danziger et al. 1979
0736+017	PKS	—	—	50	—	130	Baldwin 1975
0851+202	OJ 287	—	—	—	3.3	—	Miller et al. 1978
1308+326	B2	100	—	—	—	—	Miller et al. 1978
1400+162	MC3	—	0.6	0.3	0.6	—	Miller et al. 1978
1514−241	AP Lib	—	—	—	0.3	—	Miller et al. 1978
1641+399	3C 345	440	—	—	—	—	Visvanathan 1973a
1807+698	3C 371	—	0.4	0.1	0.6	<0.5	Miller et al. 1978
1845+797	3C 390.3	—	0.7	11	11	70	Osterbrock et al. 1976
1958+407	Cyg A	—	1.8	0.7	10	5	Osterbrock & Miller 1975
2200+420	BL Lac	—	—	—	0.08	0.06	Miller et al. 1978
2230+114	CTA 102	1200	—	—	860	—	Oke 1966
2251+158	3C 454.3	380	—	—	—	—	Visvanathan 1973a

luminosity as 3C 390.3. The structure is known to be extended over 15 arcseconds or 15 Kpc (Fomalont 1967), while all the low frequency emission in 3C 390.3 is from the double lobes with 200 Kpc separation.

3C 371 does not have such a strong low-frequency component as 0521 −36 (5 Jy at 178 MHz, and a flat 2 Jy component from 1.4–90 GHz) but its polarimetric properties have been extensively studied. Visvanathan (1967) found it to be polarized, and it has since been measured repeatedly by Dombrovsky et al. (1971), and Babadzhanyants & Hagen-Thorn (1975). Miller (1975) has recorded a high polarization of ~10%, using a small 2.4 × 4 arcsec aperture. The bulk of the available data obtained through a 26 arcsec aperture rarely exceeds 6%, presumably because of dilution by the galaxy, though Dombrovsky et al. did measure 10–12% through a 26 arcsec aperture in September 1970. At that time the source flared for a period of about a week by 0.6 magnitude to $m_B = 14.5$. The direction of polarization is certainly not constant, but nearly all measurements taken in each of seven years lie within 35° of position angle 85°.

Optical spectrophotometry of 3C 371 has been obtained by Miller (1975) who gives reference to earlier work. He identifies three optical components: a power-law continuum of index 1.35 and $m_v = 15.4$ at the time of observation; the absorption line spectrum of the galaxy; and the emission line spectrum given in Table 2.

PKS 0736+017 This is a source with strong permitted lines at $z = 0.192$, recently found to show variable optical polarization by Moore & Stockman (1980). The strength of polarization varies between 0 and 6%, with sharp changes from night to night. The optical continuum shows optical variability of more than a magnitude (McGimsey et al. 1975) and has a spectral index of 1.1 over the range 0.3–0.7 μ in the rest frame (Baldwin 1975). Line strengths by Baldwin are given in Table 2. The radio spectrum is nearly flat at ~2.5 Jy from 0.41–90 GHz.

B2 0752+258 = OI 287 = VRO 25.07.04 This object at $z = 0.446$ has recently been discovered by Moore & Stockman (1980) to show essentially constant polarization of 8% at position angle 143°. Wills & Wills (1976) found the optical spectrum to show strong sharp forbidden lines of [OII] and [OIII] but no Balmer lines, and comment that from spectroscopic evidence alone it could be classified as a galaxy, though the appearance is stellar. The only permitted line detected is the resonance doublet of Mg II. The radio spectrum known only from 0.5–2 GHz appears steep, though there is no detection at 178 MHz (<2 Jy).

1156+295 = 4C 29.45 = Ton 599 This object at $z = 0.728$ was found by Moore & Stockman (1980) to show strongly variable polarization, up to

10% in magnitude and with no preferred position angle. The optical spectrum shows strong Mg II and CIII λ1909 (Schmidt 1974), has a spectral index of 0.93 (Richstone & Schmidt 1980), and varies in brightness by at least 2 magnitudes (Moore & Stockman 1980). The radio spectrum drops slowly from 2.8 Jy at 178 MHz to 0.89 Jy at 5 GHz.

1228+127 = M87 Both the jet of polarized optical emission and the star-like nucleus of this central galaxy of the Virgo cluster are of particular interest. The optical jet is in the form of several unresolved knots out along a line from the nucleus, extending out to 25 arcsec (1.3 Kpc). Knot A, the brightest at $B = 16.8$, is about half way along the jet. Polarization was first studied photographically by Baade (1956) and photoelectrically by Hiltner (1959). Schmidt, Peterson & Beaver (1978) obtained a one-dimensional map of polarization and intensity along the jet with the 200-element Digicon detector, which allowed accurate determination of the diffuse galactic background. The knots themselves are polarized typically between 10% and 25%, with position angles apparently randomly oriented from knot to knot. Recently, Sulentic, Arp & Lorre (1979) have repeated Baade's photographs under similar conditions and find slight but significant changes in intensity and polarization of the knots, over a 22 year baseline.

In Turland's (1975) map of M87 made at 5 GHz, the radio emission from several knots is resolved, knot A having a flux of 1 Jy at 5 GHz and a spectral index of ~ 0.5. Comparing the optical and 5 GHz data, Schmidt et al. find the radio and optical polarization of individual knots agree closely in both strength and position angle, once a constant correction of 75° in angle is made for Faraday rotation. There is no detectable Faraday rotation, $\lesssim 20°$, within the knots themselves.

Sulentic et al. argue that the knots appear to be a type of BL Lac object that is ejected from the galactic nucleus. We note, though, that there are some characteristics that appear rather different: the optical variability is slower and the absolute optical flux weaker than for any known BL Lac; the radio emission is relatively steep; and no compact cores are detected in the knots in VLBI observations. As in the Crab Nebula, the optical and radio emission can be interpreted as coming from a relatively large region of optically thin synchrotron radiation. In the absence of any evidence of compact, nuclear activity within individual knots, it seems likely that the energy is being supplied in a jet from the nucleus, where there is a compact core of flatter radio spectrum with $\alpha = 0.3 \pm 0.2$ and of strength ~ 3 Jy at 5 GHz.

Turning to the nucleus, it appears that optical polarization is present intermittently. In 1971–1972, Heeschen (1973) and Kinman (1973) found variable polarization of up to 6%, measured through a 3.2 arcsec diaphragm centered on the nucleus. This would appear to be associated with the stellar object at the nucleus which is distinct from the normal stellar core of the galaxy. In 1977, Schmidt et al. found no detectable polarization, obtaining an upper limit (3σ) of 0.9% in a 1×3 arcsec aperture centered on the nucleus. In 1979–1980, R. L. Moore (private communication) obtained several measurements consistent with $0.3 \pm 0.1\%$ at 120° position angle through a 4 arcsec aperture. This last measurement was with a red-sensitive detector and would be subject to considerable dilution by the galaxy. The featureless continuum of the stellar object (Sulentic et al. 1979) and its apparent variability (de Vaucouleurs & Nieto 1979) are all consistent with weak blazar activity, but since it is not active now we shall not group it with the nearby objects of much more consistent activity. Obviously, continued polarimetric observations of the nucleus are needed. M87 is of particular interest because of the dynamical and photometric evidence of a large, central mass of $5 \times 10^9\ M_\odot$ (Young et al. 1978, Sargent et al. 1978), similar to the black hole masses inferred for BL Lac objects from the time scale of variability (Angel et al. 1978).

B2 1308+326 and AO 0235+164 These two distant ($z \sim 1$) and extremely luminous sources have many properties in common. Both are flat- or inverted-spectrum compact radio sources with no steep, low-frequency components. Both have shown outbursts in optical and radio emission lasting months, with strong, rapidly variable optical polarization. The emission lines in both cases are weak or undetectable relative to the polarized optical continuum.

Detailed studies of the polarimetric behavior of B2 1308+326 during the 1978 outburst have been made by Moore et al. (1980) and Puschell et al. (1979). The strength of optical polarization ranged up to 20%, with large variations in the strength and angle of polarization ($\Delta P \sim 7\%$, $\Delta\theta = 30°$), on a time scale of one day in the rest frame of the source. Repeated accurate measurements (typical errors of 0.25% in polarization) by Moore et al. over baselines of 2–5 hours showed only small variations consistent with the night-to-night trends. A recent reanalysis by Puschell (1980) of his data is also consistent with this result.

Moore et al. (1980) report infrared polarimetry obtained simultaneously with the optical on three different nights. On each of the three nights the strength and position angle at 2 μ and 0.6 μ are equal, indicating a common emission process. The angle of polarization is not always independent of wavelength though, since a rotation of 15° between 0.4 μ and 0.8 μ was observed on another night when only optical measurements were obtained. At centimeter wavelengths, the flux remained relatively steady during the 1978 outburst, and the polarization of a few percent was roughly constant in angle, with no Faraday rotation above 10 GHz (Puschell et al. 1979).

Only occasional polarization measurements have been made for AO 0235

+164 but these show similar variation over all position angles and sometimes great strength (20%), even when the source was faint (Rieke et al. 1976, Angel et al. 1978).

1400+162 = 4C 16.39 This object is important because it and 3C 390.3 are the only extended radio sources with central compact nuclei showing strong optical polarization known to have classic double lobe structure. The optical and radio properties have been extensively studied by Baldwin et al. (1977). The redshift of the object from weak emission lines (Table 2) is $z = 0.245$, the same as that of the brightest galaxy in a small adjacent group. The optical continuum from 2.3 to 0.5 μ is well represented by a power law of index 1.3, but then steepens to the ultraviolet. In June 1976 the V magnitude was 17.4; the object was not studied for flux variability. Optical polarization measured at Lick Observatory with the Nordsieck device over three months in 1974 was approximately constant with strength 12% and position angle 96°. Measurements in June 1978 and January 1980 by R. L. Moore (private communication) both gave 12% at 85°. A single measurement in January 1976 by Anderson and Garrison (quoted by Baldwin et al. 1977) is discrepant, 4.4% at 81°. The polarization is thus nearly steady in position angle and could perhaps be constant in strength, if the last point were in error.

Coincident with the stellar optical object is a compact radio source with a spectrum flat from 1.67 GHz (0.15 Jy) to 15 GHz (0.14 Jy). The extended structure shows approximately symmetric lobes lying along a line at position angle of approximately 115°, inclined some 20° to the direction of optical polarization. The total extent at 5 GHz is 25 arcsec, or 100 Kpc (projected on the plane of the sky), and the measured flux at 178 MHz is 2.55 Jy, extending to higher frequencies with a spectral index of 0.7.

1641+399 = 3C 345 As will be discussed in Sections V and VI, Blandford, Rees, and others have suggested that the polarized optical emission in extremely luminous polarized objects may originate in a relativistic jet directed toward us. The same type of relativistic beaming is invoked to explain superluminal expansion in compact radio sources. Thus the violently variable polarized object 3C 345, with strong emission lines at $z = 0.595$, is of exceptional interest since it shows superluminal expansion very clearly. VLBI measurements reviewed by Kellerman (1978) show two components whose separation has increased linearly from 1969–1977, at a rate of 0.17 milli arcsec/yr, corresponding to a velocity of 5 c. Only one other source in Table 1 (3C 279) is known to show superluminal expansion. In 3C 345 the position angle of the expanding double is 106°. As is often the case in other similar sources (Readhead et al. 1978), larger scale structure is not collinear.

The jet of low frequency emission lying 1–3 arcsec distant found by Davis, Stannard & Conway (1977) is at position angle 142°.

Polarization was discovered in 3C 345 by Kinman (1967), after it was found to be a radio (Dent 1965) and optical (Goldsmith & Kinman 1965) variable. The source has since been the subject of several polarimetric studies. Kinman et al. (1968) found the position angle to be about 80° during a period of high luminosity, with large changes in angle apparently correlated with short (10 day) bursts. Recently Kinman (1977) has examined all the data available over an eight-year period, and finds that the yearly polarization averages lie at approximately the same position angle (80–110°) when the source is bright. This indicates there is memory in the emission process and the angle may be related to the VLBI jet axis (105°). It is of interest that the polarization is not noticably weaker when the source is faint.

The wavelength dependence of polarization of 3C 345 was explored by Visvanathan (1973a), who found strength and angle to be constant at any given time within errors. The same result was found by R. L. Moore (private communication) using filters centered at 4500 Å and 7500 Å. Recently Knacke, Capps & Johns (1979) have reported 22–32% polarizations at 2.2 μ over a three-day period in April 1978, with no polarization detected at 1.6 μm and $P < 6\%$ at 0.44 μ. While two-component models may account for this extreme behavior, we note that the variability at 2.2 μ and in the optical is well correlated (Neugebauer et al. 1979). The spectrum from 0.3–10 μ obtained by Neugebauer et al. is close to being a single power law of index 1.4, with only a trace of the excess emission at ~ 0.3 μ and little of the complex structure common in QSOs. However, 3C 345 does appear to have some episodes when the spectrum changes, shown by Visvanathan's (1973a) multichannel spectrophotometry in which the index across the optical spectrum is seen to flatten when the source brightens.

1845+797 = 3C 390.3 This is a second key object in making the bridge between double lobe radio sources and those with variable stellar polarized nuclei. It is a classical radio double lying at $z = 0.056$ whose central galaxy contains a violently variable compact optical source (Cannon, Penston & Brett 1971) with substantial polarization ($\sim 3.5\%$). Optical polarization data over the years 1968–1973 have been published by Dombrovsky et al. (1971) and Babadzhanyants & Hagen-Thorn (1975). We will not here consider data by Efimov & Shakhovskoy (1972) which are not accurate enough to be useful. The strength of polarization measured through a 26 arcsec aperture increases with increasing brightness of the source, while remaining reasonably constant in position angle. Babadzhanyants & Hagen-Thorn (1975) make a least-squares fit to the yearly averages over

1968–1973, and obtain a best fit by superposing a source of variable intensity but constant polarization ($3.7 \pm 0.6\%$ at $155 \pm 3°$) with an unpolarized galaxy component of B magnitude ~ 16.8. In 1979, we measured the nuclear polarization in a 4 arcsec aperture to be $2.1\% \pm 0.4\%$ at 165° $\pm 5°$, consistent with the parameters given above since the remaining galaxy contribution has not been removed. An independent estimate of the underlying galaxy magnitude of $B \sim 16.6$, obtained by Penston & Penston (1973) from photometry with different aperture sizes, is also consistent with their separation model. In the radio map of 3C 390.3 given by Harris (1972) the central compact component had strength of 0.35 Jy at both 2.7 and 5.0 GHz, and is < 0.4 Jy at 1.4 GHz. Hine & Scheuer (1980) have found variability in this source on a time scale of a year. The north and south outer components are separated by 2 and 1.5 arcminutes (20 and 90 Kpc) and are unusually compact. Their strengths are respectively 7 and 17 Jy at 408 MHz and their spectral indices are both 0.85. The position angle of the source axis is 143°, quite close to the mean polarization angle of 155°. This alignment is the same as that seen in the much more luminous double lobe QSOs (see Sections III and IV).

The nucleus of 3C 390.3 shows strong, extremely broad Balmer emission lines. Spectrophotometry by Osterbrock, Koski & Phillips (1976) shows these lines having complex profiles with a full width at half-maximum of 13,000 km s^{-1} (Table 2). Polarimetric measurements of these lines are now being undertaken and will clearly be of great value in locating the origin of the optical continuum polarization.

2200 + 420 = BL Lac Not only was this object the first blazar type with no emission lines to be recognized but it exemplifies the most rapid variability of flux and polarization in its optical, infrared, and radio flux (Angel et al. 1978, Aller & Ledden 1978). We will not give here a review of the general properties of BL Lac since this is already available in the literature (e.g. Stein, O'Dell & Strittmatter 1976, Miller 1978). It lies at the center of a giant elliptical galaxy of redshift 0.067, and Miller, French & Hawley (1978) find extremely weak emission lines (Table 2).

The variability of the optical polarization has recently been studied in some detail, and has been found to rotate in position angle at rates of 1–2°/hour during a night of observing, with changes of up to 30° from night to night (Angel et al. 1978, Angel & Moore 1980). The position angle has no preferred direction. In 1979 a group of observers in America, Europe, and Israel observed the optical polarization and intensity of BL Lac for one week, with continuous coverage for more than 12 hours on most days (R. L. Moore et al., in preparation). During this week the source was being measured sometimes by four different observers simultaneously. All the data lie on a curve that varies smoothly hour by hour, but where again one day is the time scale for substantial changes. Infrared polarization measurements at 2.2 μ were obtained by Rieke and Lebofsky on two nights during this week, and also exactly tracked the optical in strength and angle. During one night when the polarization was $\sim 3\%$ a rotation of 30° during 6 hours was seen at both wavelengths. This shows that there cannot be much significant interstellar polarization arising in our own galaxy, despite its low galactic latitude. The strength and angle of polarization are not always independent of wavelength, as discussed in Section III.

2225 − 055 = PHL 5200 PHL 5200 cannot be classified as a blazar since it is radio-quiet (Mills & Little 1970) and shows no variation in its high polarization or optical flux. PHL 5200 is the prototype for a class of radio-quiet QSOs whose spectra show broad, deep absorption troughs blueward of strong resonance emission lines (Lynds 1967, Burbidge 1968). Spectropolarimetric observations show the continuum to be polarized with the lines essentially unpolarized (Stockman, Angel & Hier 1978). Thus the polarization must originate within the emission line region and is not due to dust or resonance scattering outside this region. High polarizations are not a general property of QSOs with intrinsic, broad absorption lines. We have observed three PHL 5200 type objects discussed by Turnshek et al. (1979) and all three show weak polarization, $\lesssim 2\%$.

III *Properties of Blazars*

In this section, we describe the general properties of the blazar class represented by Tables 1 and 2 in Section II. We begin with the characteristic strength and variability of the optical-infrared polarization followed by the wavelength dependence of polarization. The strong correlation of the optical polarization with photometric variability and a smooth optical-infrared continuum is discussed as are the general radio characteristics of the blazar class. We end this section pointing out correlations of the X-ray and radio properties with the presence of strong line emission.

GENERAL CHARACTERISTICS OF THE OPTICAL-INFRARED POLARIZATION

Strength and timescale of variability A primary property of the polarization is its variability; this adds richness to what can be learned from polarimetric studies, and provides job security for polarimetrists. The variations can be substantial and erratic on every time scale from a few hours on up. In addition, even for a single source the general type of variability can change. For instance, for the first year or so after its identification, OJ 287 showed polarization varying wildly in strength and angle. Since 1972, however, its polarization, although still strong, has nearly constant position angle, with the radio emission polarized at the same angle (e.g. Rudnick et al. 1978). In another case, 3C 454.3, the strong variable polarization observed a decade ago has currently vanished, and the source has settled to only 1–2% polarization (Moore & Stockman 1980). The best we can do then is to characterize the behavior of specific objects from the known data, and recognize that it may not persist.

The strength of polarization, whose maximum and minimum recorded values are given in column 7 of Table 1, has exceeded 30% in three objects (PKS 0735+178, OJ-131, OJ 287) and 20% in another nine. While it is often the most extensively measured objects that yield the highest polarization values, there are also some well-studied examples that never show very high polarization. Another polarimetric distinction that can be made among the blazars is by the range over which the position angle varies. Angel et al. (1978) found that among 12 BL Lac objects monitored polarimetrically, 5 appeared to have a definite preferred angle. Making use of all the published data referenced in Table 1, we can distinguish two types of position angle variability. One group shows no tendency for preferred angle, and data span all points of the compass. These objects are nearly all distant and extremely bright: the 3C sources 279, 345, 446, and 454.3 (during outburst), AO 0235+164, B2 1308+326, PKS 0735+178, OM 280, OJ 287 (during outburst), BL Lac. The group of objects for which repeated measurements show a restricted range of angles are 3C 66A, NGC 1275, 0422+004, 0752 +258, OJ-131, OJ 287 (recent years), Mkn 421, ON 325, 1400+162, AP Lib Mkn 501, 3C 390.3, 3C 371. These are generally less luminous objects. In Section VI, we consider the possibility that the two types of variability may reflect the difference between sources with jets pointed straight at us and those that are inclined to the line of sight.

We next turn to the time scale for changes in the polarization. Polarization measurements afford a good method for exploring variability on time scales less than a day since the linear polarization Stokes parameters Q and U change by amounts comparable to the total intensity parameter I. Rather small changes of Q/I and U/I are detected differentially to a precision limited only by photon statistics. Small changes of the total intensity I over periods of hours can only be detected by reference to standard stars, and require excellent conditions and careful treatment of extinction. Thus photometry is rarely limited by photon statistics except for the faintest objects. Variations on a time scale of a few days were recognized from the first discovery of strong polarization in the violently variable QSOs, and substantial night to night changes in the polarization of 3C 345 were measured in 1967–1968 by Kinman et al. (1968) and Visvanathan (1973a). OJ 287 also showed large nightly fluctuations in the early data of Dyck et al. (1971) and Kinman & Conklin (1971). Fluctuations on these time scales were also well established from photometric data. The synoptic study of 12 BL Lac objects made by Angel et al. (1978) with repeated measurements of the same objects during each night found that erratic variations on a time scale of a day are not uncommon in several objects but that variations from hour to hour are small. When significant hourly changes are detected they are monotonic, with dP/dt no larger than required to explain the daily variations. Thus it appears that the power spectrum of variability falls sharply for frequencies higher than 1 d^{-1}. These results have been confirmed by more recent work on BL Lac (see Section II). The variability of B2 1308+326, a source like AO 0235+164 that reaches extremely high brightness in outbursts of months duration, has recently been studied and is also discussed in Section II. The polarization changes very strongly (more even than BL Lac) on a time scale of 1 day in the rest frame of the source, but again there is no compelling evidence of much more rapid changes.

Not all strongly polarized sources show detectable variability; a few appear to be essentially constant in both strength and angle. OI 287 has been virtually constant with 8% polarization at 145° over a two year baseline (Moore & Stockman 1980), 3C 66A shows slight changes in polarization, but virtually all data points lie within $12 \pm 2\%$ in strength and $30 \pm 16°$ in angle. The double lobe radio source 1400+162 (see Section II) has polarization 12% at close to 90° for all but one measurement.

Wavelength dependence of polarization Another property of the polarization of considerable interest is its dependence with wavelength across the optical-infrared spectral range. It has long been known, particularly from the work of Visvanathan (1973a), that the polarization is usually wavelength independent at least across the optical spectrum. Sometimes, though, some objects do show small but significant rotations in position angle of up to 15° (Rieke et al. 1977, Moore et al. 1980), or changes in strength of polarization from blue to red (Kikuchi et al. 1976, Nordsieck 1976). The smoothness of the continuous emission from the optical to the infrared suggests that the infrared emission (where most energy is released) should share the polarimetric properties of the visible spectrum. This has recently been found to be the case. Simultaneous or nearly simultaneous observations of polarization over the range 0.4–2.2 μ have been reported for AO 0235, PKS 0735+178, OI 090.4, OJ 287, B2 1308+326, 3C 345, and BL Lac, in papers by Knacke, Capps & Johns (1976, 1979), Rieke et al. (1977), Puschell et al. (1979), Moore et al. (1980), and Puschell & Stein (1980). Generally the polarization is found to be the same in both strength and angle, but there are observations of substantial rotation of position angle (e.g. 35° in

OI 090.4) from the optical to the infrared. Until recently, no marked color dependence in the strength of polarization had been found, but some recent observations of BL Lac (Puschell & Stein 1980) and 3C 345 (Knacke et al. 1979; Section II) showed a strong increase to the ultraviolet in the former, to the red in the latter.

CORRELATION OF STRONG OPTICAL POLARIZATION WITH OPTICAL-INFRARED CONTINUUM PROPERTIES There seems to be virtually a one-for-one correspondence between the occurrence of polarization and large fluctuations in the optical flux. Essentially every object in Table 1 that has been monitored extensively shows variations larger than a magnitude. Conversely, almost all objects known to exhibit large fluctuations in brightness are found to be strongly polarized. For instance, in Usher's (1975) table of variable QSOs and BL Lac objects, there are 13 objects with $\Delta B > 2$ magnitudes. Eleven of these are in common with Table 1, one is in the south and has not been measured for polarization, and only one, 3C 323.1, is not strongly polarized. The correspondence is not perfect and a few variable objects are found not to be polarized (e.g. 3C 120 with $\Delta B = 1.7$). Selection effects play some role in this correlation, as some outstanding examples were originally picked out for polarimetric study after their variability was discovered. 3C 446, the first QSO found to be polarized, was measured by Kinman et al. (1966) after variability was discovered; the identification of BL Lac as an inverted-spectrum radio and optical variable (MacLeod & Andrew 1968, Schmitt 1968) led to the discovery of optical polarization. Nevertheless, many high polarization objects were identified from radio surveys before their optical variability was studied.

A second striking correlation of optical polarization is with the shape of the optical-infrared continuum. The fact that the optical spectrum of polarized objects tends to be steeper than that of most emission line QSOs has been recognized for some time (e.g. Stein, O'Dell & Strittmatter 1976). Now that good photometry from 0.3–10 μ has been obtained for many Seyfert nuclei, BL Lac objects, and QSOs, we find a division can be made between those that can be well represented by a simple power law or spectral shape, and those that have complex shapes (Rieke & Lebofsky 1979). The former class is virtually coincident with the class of highly polarized objects we are considering. The recent spectra of bright QSOs by Neugebauer et al. (1979) illustrate this very well. Picking out the straight spectra from the sample of 30 objects, one finds they are just the group of classical violent variable QSOs (3C 279, 3C 345, 3C 446, 3C 454.3). 3C 68.1 has the only other smooth spectrum in the sample, and its polarization has not yet been measured. Puschell (1980) remarks that there are no objects known showing correlated variability in the optical and infrared that are not highly polarized. Thus 3C 120 fails as a blazar not only in lacking polarization, but also in showing infrared radiation which does not track the optical on short time scales (Rieke & Lebofsky 1979).

RADIO EMISSION OF BLAZARS An outstanding property we see from Table 1 is that all entries except PHL 5200 show radio emission, a correlation supporting the idea that nonthermal processes are responsible for the polarization. Historic interest in radio sources has biased most polarization surveys toward the discovery of radio-loud objects. Nevertheless the correlation of radio emission with the optical properties of polarization, strong variability, and smooth spectra is not a result of selection effects. Among emission line objects large numbers of radio-quiet QSOs searched by Stockman & Angel (1978) and Stockman (1978) yielded PHL 5200 as the only strongly polarized radio-quiet QSO. Seyferts, which are nearly all very weak radio sources, in the study by Maza, Martin & Angel (1980), showed exclusively dust type polarization, with only one or two possible exceptions (see Section IV).

Since nearly all known BL Lac objects are from radio surveys (Condon 1978) the observational bias against radio-quiet BL Lacs is severe. Certainly in one case, I Zw 186, the unusual bright featureless nuclear continuum was discovered by Zwicky (1966) while observing compact galaxies, and optical variability was then found by Oke et al. (1967) and Sandage (1967), still before weak radio emission was detected (Altschuler & Wardle 1976). Mkn 501 is another object noticed first by its unusual featureless spectrum, in a survey of Markarian galaxies by Khachikian & Weedman (1974). It then proved to have a flat radio spectrum and strong variable polarization. X-ray emission is not well correlated with radio emission at the lower frequencies of most radio surveys (see below), so one might hope that X-ray surveys would find radio-quiet objects. All-sky X-ray surveys have discovered at least one source (2155 – 304) not previously recognized, but this again has proven to be a radio source. From these data, it seems likely that if radio-quiet BL Lac objects exist, then they must be considerably less numerous than radio-loud ones. This situation is of course the reverse of that for emission line QSOs, where the radio-quiet QSOs far outnumber the radio-loud.

Having noted the common feature of radio emission for the objects in Table 1, we must go on to point out that the character of the emission varies widely among different sources. Nearly all have a flat-spectrum component, but there is a large range in luminosity. Five objects are among the intrinsically brightest of all known sources at 2700 MHz. 3C sources 279, 345, 446, 454.3, and CTA 102 all have apparent luminosities (assuming isotropic emission) of $\sim 10^{35}$ ergs Hz^{-1} s^{-1}, and constitute about 20% of all sources known to be this luminous. By contrast the faintest objects such as Mkn 180 have luminosities of 10^{31} ergs Hz^{-1} s^{-1}. It is interesting that the most direct evidence for bulk relativistic motion is only for the intrinsically brightest objects. The two certain cases of superluminal expansion that are known for objects in Table 1 are from this group, namely 3C 345 and 3C 279. Also, the only examples in Table 1 of low-frequency variability (which suggests bulk relativistic motion—see Section V) are 3C 454.3, CTA 102, and PKS 0420−014, which is also very bright. AO 0235+164 is so bright and rapidly variable at high radio frequencies that, again, brightness temperatures in excess of 10^{12} K are indicated. For the fainter objects with absent or weak emission lines (BL Lacs), VLBI data is reviewed by Shaffer (1978). Changes in structure are seen, but there is no strong case of superluminal expansion.

Radio structure on scales of arcseconds or larger, generally with steep spectra, has been measured in the following objects: NGC 1275 (Miley & Perola 1975), PKS 0521−365 (Fomalont 1967, Mills, Slee & Hill 1960), AO 0827+24 (Hazard, Gulkis & Sutton 1968), Mkn 180 (Kojoian et al. 1976), 1400+162 (Baldwin et al. 1977), AP Lib (Conway & Stannard 1972), 3C 345 and 3C 454.3 (Davis, Stannard & Conway 1977), 3C 371 (Fomalont & Moffet 1971), and 3C 390.3 (Harris 1972). Extended structure of 10–200 arcsec extent, generally of steep spectrum, is also known to be present in about half the sample of 27 BL Lac objects studied by Wardle (1978). Details of this structure are not known because the interferometer was used at only one position angle. Since symmetric extended radio emission, like the optical line emission, is almost surely isotropic, the geometry and strength of the extended sources can aid in distinguishing the degree to which relativistic beaming may be present, and will be considered further in Section VI.

Variability and polarization at radio wavelengths have quite different characteristics for different objects in Table 1. From the four year monitoring program by Altshuler & Wardle (1976) one finds that the optically violently variable quasars 3C 454.3, 3C 446, 3C 345, and CTA 102 generally have rather steady flux and polarization. By contrast, the BL Lac objects 0048−09, 0235+16, 0300+47, OJ 287, W COM, 1749+096, 2155+304, and BL Lac are strongly variable in both flux and polarization. Unfortunately there is little data for the nearby objects with $z < 0.1$, except for BL Lac, NGC 1275, whose radio emission is essentially unpolarized, and AP Lib, which has relatively steady polarization. Coordinated observations of blazars from radio through optical wavelengths by Rudnick et al. (1978) show the polarization is generally weaker at radio wavelengths. With the exception of OJ 287, for most blazars there is little correlation between the angles of optical and radio polarization.

CORRELATION OF RADIO AND X-RAY EMISSION WITH OPTICAL EMISSION LINES IN BLAZARS There is a strong correlation between the radio emission of blazars and their optical emission lines. Consider the group of all eleven objects in Table 1 with $z < 0.1$, all of which are found at the center of giant elliptical galaxies. The five of them (Mkn 180, 421, 501, I Zw 186, 0548 − 322) that have no detectable emission lines all show the weakest radio emission, all of similar strength with flat spectra at ~0.5 Jy scaled to a common z of 0.05. The remaining six objects that do show emission lines are 3C 84 (NGC 1275), 3C 371, 3C 390.3, PKS 0521 − 36, BL Lac, and AP Lib. All show stronger radio emission, at least 2 Jy at 1400 MHz, again scaled to $z = 0.05$, and all but BL Lac have a low-frequency steep-spectrum component.

The correlation between the presence of detectable emission lines and of a steep component to the radio spectrum holds for nearly all objects in Table 1, without regard to redshift. Another general correlation we have mentioned above is that the emission line objects tend to have relatively stable radio polarization and flux, in contrast to the line-free objects.

In contrast to the radio correlation, the X-ray emission observed from some of the same 11 objects is not stronger for those with lines, indeed there is a suggestion that the line-free objects may have stronger X-ray fluxes. The highest X-ray luminosities of > 5 μJy at 3.6 keV, referred to $z = 0.05$, have been observed in Mkn 521 and PKS 0548 − 322, both line-free objects. All the line-free objects except Mkn 180 have been detected at the ~1 UHURU count level, making the X-ray and optical luminosities comparable.

IV *Active Objects with Low Polarization*

As mentioned in the introduction, most active extragalactic objects show optical and infrared polarization of a percent or less. At these low levels, the case for any detected polarizations being intrinsic to the nuclear emission is much weaker than for the blazar class. The polarization may also be due to scattering by dust or free electrons or due to transmission through aligned grains either in the host galaxy or in our own. In the first half of this section, we review the polarimetric observations of Seyfert galaxies, where there is good evidence that the polarization is due to dust. Thus, rather than include the highly polarized Seyferts with sources of intrinsically polarized emission in Sections II and III, we discuss them here. For the majority of QSOs, whose polarizations are quite low, the source of the residual polarization is unknown. We review recent survey work of QSOs in the second half of this section.

SEYFERT GALAXIES Since the most detailed polarimetric observations to date have concentrated on two of the brightest Seyferts, NGC 1068 and NGC 4151, these are reviewed separately below. The first general polarization surveys of Seyferts were undertaken by Dombrovsky, Hagen-Thorn, and other collaborators and are summarized in Dombrovsky & Hagen-Thorn (1968), Dombrovsky et al. (1971), and Babadzhanyants & Hagen-Thorn (1975). This work has also been reviewed by Hagen-Thorn (1974) and in Maza's dissertation (1979). Although most of these observations utilized a rather large aperture (26″) which resulted in severe galaxy dilution of the nuclear light, these authors correctly attributed the observed polarization to the nuclear light, and found the strong wavelength dependence of polarization in NGC 1068 and NGC 4151, and detected weak polarization in NGC 3227 and NGC 7469 and several others. Because of the variable polarization observed in NGC 1275 (Section II) and NGC 4151 along with the nonthermal radio emission observed in NGC 1275 and other radio galaxies classified as Seyferts, the polarization was generally attributed to optical synchrotron radiation. However, a more recent polarization survey by Maza, Martin & Angel (1980) and spectropolarimetric work of several groups indicate that this is not the case.

Maza, Martin & Angel's survey of 47 Seyferts found only 8 with polarizations greater than 1.5% in a 4″ aperture: 5 Type 1's—Mkn 231, Mkn 486, Mkn 376, NGC 6814, IC 4329A; and 3 Type 2's—NGC 3227, Mkn 348, and Mkn 3. [Note: the polarization in NGC 6814 is probably local interstellar polarization (Maza 1979).] Additional multicolor polarimetry showed that most highly polarized Seyferts have stronger polarization in the blue than in the red with little rotation of position angle with wavelength. Spectropolarimetry of Mkn 376, IC 4329A, Mkn 231, NGC 3227, Mkn 3, and NGC 3516 (Stockman, Angel & Beaver 1976, Thompson et al. 1980) show that the emission lines and continuum in these sources have similar polarizations. Together with the strong wavelength dependence of polarization, this argues for dust scattering (see NGC 1068 below) or in at least one case, IC 4329A, an edge-on spiral, for transmission through aligned grains as the origin of the optical polarization. The case for polarization due to dust is not as strong for those few sources with a polarized continuum but unpolarized emission lines (e.g. NGC 4151 below, and our preliminary results for Mkn 486).

We must emphasize that observations of generally weak polarization in Seyferts and the absence of strong radio emission do not rule out the possibility of nonthermal emission in the nuclei that has been reprocessed inside the emission line region or diluted by thermal emission. Indeed, the high X-ray luminosities associated with most of the bright Seyferts (with the notable exception of NGC 1068) argue for a non-stellar origin for much of the optical infrared emission (Mushotzky et al. 1980, Dower et al. 1980).

NGC 1068 NGC 1068, a Type 2 Seyfert (narrow emission lines, FWOI ~ 1000 km s^{-1}), has had its optical polarization repeatedly measured by

Walker (1964, 1968), Dibaj & Shakhovskoy (1966), Kruszewski (1968), and by Dombrovsky and collaborators (see above). Apart from the early, rather crude measurements, the optical polarization and luminosity of the nucleus appear constant. The polarization measured through a $2''$ aperture increases toward the blue, roughly as $P \propto \lambda^{-3}$ from $\sim 0.6\%$ at $0.8\ \mu$ to $\sim 11\%$ at $0.32\ \mu$. The position angle increases gradually from $\sim 94°$ to $102°$ over the same spectral range (Angel et al. 1976).

Using data obtained through a large aperture ($\sim 10''$) Visvanathan & Oke (1968) and Kruszewski (1968) found the polarized flux to be essentially constant with wavelength, suggesting a flat, nonthermal component to the nuclear light. However, spectropolarimetric observations by Angel et al. (1976) showed the polarization of the permitted emission lines to be similar to that of the surrounding continuum. This evidence, together with the strong wavelength dependence and the observed large ellipticity, strongly point to dust scattering as the polarizing agent (see Section V). Infrared observations by Knacke & Capps (1974) and Lebofsky, Rieke & Kemp (1978) indicate strong wavelength dependence on degree and position angle of polarization in the spectral range 1.2–10 μ which may be due to an added nonthermal component in the region 1–5 μ or a complex cloud geometry around the nucleus (Jones et al. 1977, Elvius 1978). While NGC 1068 is the best-studied Seyfert, Maza (1979) points out that in visible light its core luminosity is very weak relative to the host spiral galaxy. If it were at redshifts typical of the majority of known Seyferts, its polarization would be practically undetectable, being less than 0.5% with the $4''$ aperture used in the survey.

NGC 4151 The spectrum of NGC 4151 shows strong narrow and broad emission line components and is generally classified as a Type 1 Seyfert (FWOI $\gtrsim$ 5000 km s^{-1}). Unlike NGC 1068, the nuclear luminosity and degree of polarization of NGC 4151 does vary on a time scale of years, though with little change in the position angle (Dombrovsky & Hagen-Thorn 1968, Babadzhanyants, Hagen-Thorn & Lyutyi 1972, and Kruszewski 1977). The degree of polarization is small, $\sim 1\%$, and is roughly independent of wavelength into the near infrared, where it falls to $\sim 0.1\%$ at 2.2 μ (Kemp et al. 1977). Spectropolarimetric observations by Thompson et al. 1979 and Schmidt & Miller (1979) show the polarization of both the broad and narrow emission line components are much weaker than that of the surrounding continuum. These observations are consistent either with nonthermal continuum diluted by thermal emission and starlight or with scattering within the broad-line emission region.

While the weak but variable polarized component of the optical continuum in NGC 4151 resembles that seen in the blazars, it should be noted that the radio emission is far weaker than any object in Table 1. In addition, the radio source is not compact but is extended over ~300 pc, with a steep spectrum. De Bruyn & Willis (1974) observed a flux of 0.135 Jy at 5 GHz with a spectral index of 0.74.

QSOs Polarimetrists who first searched quasi-stellar sources for the high polarizations expected from synchrotron radiation were rewarded with the strong and rapidly variable polarization of the optically violent variables 3C 345, 3C 446, 3C 454.3, 3C 279 (Section II). Other QSOs such as 3C 273 (e.g. Whiteoak 1966, and Liller 1969) had disappointingly low polarizations. More extensive polarimetric surveys by Appenzeller & Hiltner (1967) and Visvanathan (1968) failed to discover any additional strongly polarized QSOs. The sensitivity of these surveys was such, however, that polarizations of a few percent could not be unambiguously detected.

Recently, Stockman & Angel (1978) have reported preliminary results of a large polarimetric survey of bright QSOs, $V \gtrsim 17$ (see also Stockman 1978). They find that ~90% of this sample have low polarizations, <2%. Much of the average polarization, ~0.6%, is due to local interstellar polarization. With the exception of the unusual object PHL 5200 (Section II), none of the radio-quiet QSOs are strongly polarized. Since the vast majority of QSOs are believed to be radio quiet, the blazar type must be extremely rare. Indeed, the gap in polarimetric properties between the few strongly polarized ones and the remaining QSOs (even radio emitters) suggests that the blazar QSOs are a qualitatively distinct subclass of objects (Sections II and V).

The origin of the small polarizations seen in the majority of QSOs is unknown. Multicolor observations indicate that, while there is a statistical tendency for the polarizations to increase to the blue, the optical polarization is essentially wavelength independent (Moore, Stockman & Angel 1980). The weak polarizations and their lack of marked wavelength dependence suggests that, unlike Seyfert nuclei, QSOs have little surrounding dust ($\tau \ll 1$).

Stockman, Angel & Miley (1979) found that in those QSOs with double radio lobes the position angle of polarization was roughly aligned with the radio structure. Thus, unlike the most variable blazars, the position angle must be relatively constant for time scales of 10^6–10^7 yrs.

As with the Seyfert galaxies, the lack of strong polarization does not preclude a luminous nonthermal central source. Tananbaum et al. (1980) find many QSOs with an X-ray luminosity comparable to their optical-infrared luminosity, thus indicating a powerful, nonstellar engine. However, the very weak polarizations do argue for efficient reprocessing of any nonthermal optical emission or for dilution by an unpolarized, isotropic source which is probably thermal (Section V). More detailed study of the low polarization sources (wide baseline multicolor and spectropolarimetric observations; continued monitoring) will give valuable information concerning the origin of the polarization and should be capable of distinguishing between reprocessing and thermal dilution models.

V *Theoretical Models and the Origin of Polarization*

Of all active extragalactic objects, the blazar class exhibits the most extreme behavior in variability and polarization and places the greatest burden on current theoretical models of the central powerhouse. In this section, we review current theories with an emphasis on those areas pertaining to optical polarization and rapid variability. We devote the majority of the section to discussing basic emission mechanisms and, in particular, the canonical incoherent synchrotron model. After reviewing its success at describing extragalactic radio sources, we examine the difficulties of extending the theory into the optical, in addition to the well-known problems with the low-frequency variables, superluminal expansion, and short particle lifetimes—all of which are associated with the blazar class. Although the incoherent synchrotron theory and the alternative emission mechanisms are intimately connected to specific models for the central source of energy, we postpone discussing models for the central powerhouse and their common features until later in this section. Finally, we briefly review the processes by which dust scattering can cause linear and circular polarization.

INCOHERENT SYNCHROTRON RADIATION Because of its success in explaining the radio emission from the Crab Nebula, incoherent synchrotron emission was proposed by Shklovsky (1955) and others to be the source of the diffuse extragalactic radio emissions whose power-law spectra at high frequencies (optically thin regime) resembled that of the Crab. The synchrotron theory was soon extended to the compact sources, whose flat spectra are generally considered to be the superposition of many components of varying optical depth (see, for example, Kellermann & Pauliny-Toth 1968). One of the successes of this canonical theory of incoherent synchrotron theory was its "prediction" of the upper limit of observed brightness temperatures, implied by the observed flux and VLBI measurements or limits on angular size, $T_b \lesssim 10^{12}$ K. Such temperatures indicate that relativistic electron energies, coherent plasma effects, or both must be present. In the canonical theory, the maximum brightness temperature of $\sim 10^{12}$ K corresponds to the onset of significant Compton upscattering of the synchrotron radiation by the relativistic electrons. At higher brightness temperatures, the upscattered photons are themselves upscattered in energy leading to a "Compton catastrophe" and rapid cooling of the relativistic electron distribution (Hoyle, Burbidge & Sargent 1966, Kellerman & Pauliny-Toth 1969, Jones, O'Dell & Stein 1974). In addition to explaining the observed power-law spectra and surface brightness limits, the canonical synchrotron theory also predicts high polarizations (60–80%; Korchakov & Syrovatskii 1962) in the optically thin regions. Although radio sources generally show much lower polarizations, these could be understood as resulting from chaotic field geometries and self-absorption effects (Jones & O'Dell 1977a).

Despite the success of the canonical theory in describing the compact- and steep-spectra radio emission, there is little evidence that the observed optical emission from the large majority of QSOs or Seyfert nuclei is a simple extension of the observed radio emission (Section IV) or is even nonthermal in origin. For the blazar class, however, their smooth spectra, high polarization, and rapid variability make the incoherent synchrotron theory look more promising (Section III). In particular, rather simple models for the source can explain the observed polarization properties. For example, the presence of many misoriented emission regions with equal strength magnetic fields and particle distributions will produce a reduced net polarization that is independent of wavelength. Another model was explored by Nordsieck (1976) in which the field is preferentially stronger in one direction. In this case, the polarization depends on the electron energy distribution with the result that strong polarization should be associated with steep optical spectra and a convex curved spectrum will show polarization increasing to the blue. While indeed the blazars do tend to have steep spectra, recent observations do not support these specific predictions. Simultaneous infrared and optical measurements, summarized above, show polarization that is usually wavelength independent, even in BL Lac which falls steeply in the optical. We also find that several of the sources in Table 1 that show strong polarization have relatively flat spectra (Sections II and III).

Beyond explaining the spectral and polarization properties of the optical emission, the extension of the incoherent synchrotron spectrum into the optical region places several severe constraints on the emission source. For rapidly varying ($t_{var} \sim 1$ day), luminous sources ($\nu F_\nu \sim 10^{46}$ ergs s^{-1} or $L_{46} \sim 1$) the corresponding brightness temperature in the optical ($\nu \sim 10^{15}$) is $T_b \gtrsim 1 \times 10^5$ K. For a spectral index of 0.5–1, we would expect the corresponding radio spectrum to be self-absorbed ($T_b \sim 10^{12}$ K) in the frequency range 2–5 $\times 10^{12}$ Hz or $\lambda \sim 60$ μm in the far infrared. Thus the variable optical-infrared sources must be smaller than the observed radio components. Although relativistic beaming or lower luminosities may weaken this argument, in general we would expect little or no correlation between the optical and radio spectral bands on time scales of a week or less. As well as being more compact, the optical region must also have stronger fields. To avoid the Compton catastrophe, the lower limit to the magnetic field is given by Blandford & Rees (1978) $B_c \sim 125\, L_{46}^{1/2}\, t_{var}^{-1}$ gauss (here t_{var} is in units of one day). Blandford & Rees also derive a cooling time due to synchrotron radiation followed by mildly relativistic cyclotron radiation $t_{cyc} \lesssim L_{46}^{-1}\ t_{var}^{2}$ hr. Since $t_{cyc} < t_{var}$ for the rapid variations observed in most blazars, the electrons must be reaccelerated many times on a variability time scale if the density of thermal electrons is not to exceed the number of relativistic electrons. To avoid any significant Faraday rotation, the reacceleration may need to be almost continuous in the most variable sources. In the radio emission regions, the absence of Faraday rotation places an even more stringent upper limit on the number of nonrelativistic electrons, $n(\gamma < 100) \ll n(\gamma > 100)$ (Wardle 1977, Jones & O'Dell 1977b, see also Noerdlinger 1978).

BEAMING AND RELATIVISTIC JETS Two types of behavior found among the blazars, low-frequency variability with brightness temperatures inferred from variability arguments far exceeding 10^{12} K (Condon et al. 1979) and superluminal expansion (Cohen et al. 1979), present serious difficulties for the canonical incoherent synchrotron theory. Many remedies have been offered: non-cosmological distances (Hoyle, Burbidge & Sargent 1966); anisotropic electron distributions (Woltjer 1966); coherent emission processes (see below); and various phase and absorption effects (Rees & Sciama 1965, Jones, O'Dell & Stein 1974). One promising group of theories employs the relativistic Doppler effects present when a relativistic jet of plasma is viewed "end-on" (Lovelace 1976, Rees 1978b, Blandford & Königl 1979, Scheuer & Readhead 1979, Marscher 1980). Not only can these effects explain apparent superluminal velocities but the forward-beaming and time-dilation effects can increase the apparent radio brightness temperatures by very large factors ($T_{obs} \sim 10^2$–$10^3\ T_{true}$ for $\gamma \sim 5$–10; Blandford & Königl 1979). Recent VLBI observations indicate that many radio doubles have well-collimated structures on scales of 1 pc–1 Mpc (e.g. Readhead, Cohen & Blandford 1978). In addition, the lack of interstellar scintillation in the low-frequency variables provides indirect evidence for relativistic bulk motions (Condon & Dennison 1978). In the comoving frame of the relativistic jet, the dominant emission mechanism is still thought to be incoherent synchrotron emission. For observers essentially on axis ($\theta \lesssim \gamma^{-1}$), special relativistic effects will shift the spectrum blueward, enhance the luminosity, and decrease the observed time scales for variability (Rees & Simon 1968, Burbidge, Jones & O'Dell 1974). In addition, small variations in the beam direction may appear as quite large changes in the position angle of polarization, with 180° variations expected for end-on views. Blandford & Königl (1979) and Blandford & Rees (1978) suggest these relativistic effects may be responsible for the optical as well as radio properties of AO 0235+164 and other BL Lac objects.

COHERENT RADIATION S. A. Colgate and collaborators have suggested a coherent emission process that is capable of describing the qualitative features of the radio, optical, and X-ray spectra and permits brightness temperatures far in excess of 10^{12} K (e.g. Petschek, Colgate & Colvin 1976). Coherent emission at $\nu \sim 2\nu_p$ is produced and frequency-scattered by nonthermal plasma oscillations in a mildly relativistic, thermal gas ($kT_e \sim 1/2m_ec^2$). Coherent and incoherent Compton scattering then produce the low-frequency and high-frequency (optical) radiation. Thermal bremsstrahlung is chiefly responsible for the observed hard X-ray spectrum.

Because the optical photons are created through multiple Compton scatterings, this model has great difficulty explaining the high polarization and variability of polarization that characterizes the blazar class (as does the electron scattering model suggested by Katz 1976). An important constraint on these scattering models is the very low upper limit on the net magnetic field set by the lack of observed Faraday rotation in the radio, $B \leqq 10^{-7}$ G (Colgate & Petschek 1978). Jones, O'Dell & Stein (1974) review the energetic problems of other coherent emission models.

THERMAL PROCESSES There is a great amount of evidence, especially in Seyfert galaxies and in the unpolarized QSOs, that the nonthermal optical-infrared radiation has been diluted by thermal emission or reprocessed. Infrared studies of the variability and 10 μ features of nearby Seyfert galaxies indicate that most of the luminosity in both Type 1 and 2 Seyferts is due to thermal reradiation by dust (Rieke & Lebofsky 1979). Polarimetric evidence in support of dust is discussed in Section IV and reviewed by Maza (1979) and the high hydrogen column densities derived from recent X-ray data (Mushotzky et al. 1980) also indicate that absorption and scattering by dust may be important in these objects. For most QSOs, the nature of the infrared emission is unclear. Recent infrared-optical observations by Neugebauer et al. (1979) indicate significant structure and changes in the spectral slope in those QSOs that are not known polarized variables (see Section III). The complex spectra may be due to either thermal continuum emission from the photoionized regions responsible for the strong line emission seen in the objects (see the recent review by Davidson & Netzer 1979), reradiation by dust, or optically thick radiation from an accretion disk (Shields 1978).

A series of authors have suggested that Compton scattering from a hot gas ($kT_e \sim 5$–100 keV) may play an important role in reprocessing the nonthermal synchrotron spectrum (Katz 1976, Stockman 1978, Eardley et al. 1978). The scattering will tend to destroy any intrinsic polarization and variability and will harden the emergent spectrum. Thus these models are also more relevant for the nonpolarized sources.

MODELS OF THE CENTRAL POWERHOUSE The tremendous luminosities of bright QSOs, $L \sim 10^{46}$–10^{48} ergs s^{-1}, are generally thought to be gravitational in origin. Models that invoke thermonuclear burning are usually inefficient and are incompatible with the high polarizations and rapid variability displayed by the blazar class. These blazar properties, the observed radio jets, and Eddington luminosity arguments suggest a central aligned supermassive object, $M \sim 10^8$–$10^{10}\ M_\odot$, either a magnetically and rotationally supported "spinar" (Pacini & Salvati 1978) or accretion onto a black hole (Rees 1978a).

Estimates of the ages for the double radio lobes and their alignments with the central VLBI sources and the optically polarized QSOs (Stockman, Angel & Miley 1979) require alignment of the central source over time scales of $\gtrsim 10^7$ years. For accretion onto black holes, the required accretion rate is $\dot{M} \sim 2\eta^{-1}\ L_{47} M_\odot$/year where η is the efficiency. For steady luminosities less than the Eddington limit, the lower limit on the mass of the black hole is $M \gtrsim L_{47}\ 10^9\ M_\odot$. The alignment of the rotation/jet/polarization axis will be maintained for time scales of $\sim M/\dot{M} \gtrsim 4 \times 10^8\ \eta$ years (Rees 1978b). It is interesting to note that an *upper* limit on the mass of the central source can be obtained from equating the variability time scale ($t_{\rm var}$ (days) ~ 1) with the light travel time across a Schwarzschild radius, $M \lesssim t_{\rm var} 10^{10}\ M_\odot$ (Elliot & Shapiro 1974, Moore et al. 1980). Relativistic beaming effects can raise this upper limit by approximately the Lorentz factor.

The relativistic particles required to explain the observed nonthermal radiation are generated by strong electromagnetic fields in spinar or some accretion disk models (e.g. Lovelace 1976) or by nonequilibrium processes (turbulence, relativistic shocks, Fermi acceleration, etc.) in the region near the black hole where $v_{\rm infall} \sim 1/2c$ ($E \sim 100$–200 MeV/nucleon). In this regime, the emission is likely to be dominated by nonthermal processes rather than bremsstrahlung.

Details of the accretion process and the formation of a relativistic jet are extremely uncertain. Disk models have been suggested by Lynden-Bell & Pringle (1974), Blandford (1976), Eardley et al. (1978) and others. Electromagnetic and hydrodynamic models for the formation of relativistic jets are discussed by Blandford & Rees (1974), Lovelace (1976), and Blandford (1976).

POLARIZATION BY DUST SCATTERING The production of polarization by dust scattering is a well-known phenomenon that has been well studied in our own galaxy and is recently discussed by Martin (1979). Light transmitted through grains aligned by a magnetic field becomes linearly polarized, the effect responsible for the interstellar polarization of reddened stars. As in our own galaxy, the magnetic field of external galaxies appears to be in the direction of orbital motion (Elvius 1972). If light from a galactic nucleus were polarized by transmission through aligned grains in a spiral host galaxy, viewed nearly equatorially, we would expect the polarization to be parallel to the galaxy's major axis. If the grains are of a similar size to those causing polarization in the Milky Way, then polarization peaking in the visible part of the spectrum is a characteristic signature.

Polarization is also produced in the light that is scattered off small grains, regardless of their orientation. In some nuclei the very strong thermal radiation in the infrared shows the presence of optically thick dust, and most of the visible light must be scattered before leaving. Any departure from spherical symmetry will then result in net polarization of the source. This process is likely responsible for most of the polarization of Seyfert nuclei, including the strongly polarized ones where emission lines and continuum all share the same polarization. The very strong increase of polarization to the ultraviolet in most of these is probably indicative of scattering by very small particles (i.e. Rayleigh scattering).

When the scattering optical depth exceeds unity, multiple scattering in a skew geometry can produce significant circular polarization if the grains are not too small. In NGC 1068, the observed ellipticity, amounting to nearly 5% in the red, is probably due to this mechanism (Angel et al. 1976). For most active extragalactic objects with low linear polarization, circular polarization due either to scattering or synchrotron self-compton effects (Sciama & Rees 1967) is expected to be very small in the optical, $\lesssim 0.1\%$. This is consistent with current observational limits (Landstreet & Angel 1972, Kemp, Wolstencroft & Swedlund 1972, Maza 1979).

VI *Relativistic Jets and Optical Polarization*

We have reviewed in Sections III and V the suggestion by Blandford & Rees (1978) that in AO 0235+164 and similar objects relativistic jets may be responsible for beamed polarized optical radiation, as well as the very high radio brightness temperatures and apparent superluminal expansion. If the superluminal sources are beamed with cone angle of $\sim 1/\gamma$, and $\gamma \gtrsim 5$ is required for the more more rapidly separating doubles, then for every source beamed toward us there must be $\gtrsim 100$ sources at the same distance with misdirected beams. Analyzing the source counts for QSOs, Scheuer & Readhead (1979) identify these two classes as radio-loud flat-spectrum quasars, and the much larger number of radio-quiet objects. The radio emission from double-lobe or extended steep-spectrum sources is not beamed, so the statistics of occurrence of central flat-spectrum sources in such sources can be used to measure independently the degree of beaming. Scheuer & Readhead find $\gamma \lesssim 2$ by this method.

In this section we consider the arguments that can be made for the rapidly variable, highly polarized optical emission characteristic of blazars being produced in relativistic jets. The situation is closely related to but somewhat different from the radio emission. As we have seen, the ratio of polarized optical flux to high-frequency radio emission varies by over a thousand from flat-spectrum QSOs with no polarized optical emission, through violent QSOs like 3C 345, to weak radio sources like Mkn 421.

From the objects listed in Table 1 we can distinguish two types that must be inherently different, irrespective of any possible beaming. These are the strong emission line objects, and the generally weaker BL Lac (weak-lined or line-free) types. The first group contains the violent variable QSOs that are apparently strongly beamed, 3C 345 with superluminal expansion $v = 5\,c$ and 3C 279 with $v \simeq 10\,c$ (Cotton et al. 1979). There are also another dozen or so strong-lined sources in Table 1 for which there is no direct evidence of relativistic beaming, but which have similar luminosity and variability of polarized radiation. The space density out to $z = 0.7$ of these objects is $\sim 1/\mathrm{Gpc}^3$, allowing for incomplete coverage in the south. If we assume that these sources are all beamed towards us with γs of ~ 5 and corresponding (half) cone angles of 0.2, then the space density of misdirected sources would be $\sim 40/\mathrm{Gpc}^3$. This is close to the density of $140/\mathrm{Gpc}^3$ found for local QSOs down to the lowest luminosity class of $L_{\mathrm{opt}} = 10^{46}$ ergs s^{-1} considered by Schmidt (1978). Thus we reach a conclusion similar to that of Scheuer & Readhead. If relativistic beaming is responsible for the strong polarization seen in some QSOs, then most QSOs, including radio-quiet ones, must be emitting misdirected beams of polarized light.

If this picture is correct, then there are some interesting consequences. All these essentially identical strong line objects would be emitting most of their energy in the optical-infrared spectrum as isotropic unpolarized emission with the characteristic complex spectral structure, very possibly from thermal emission in an accretion disk (Shields 1978). The energy in the beam, since it does not swamp the emission lines even when directed toward us, is a small fraction of the QSOs energy budget when Doppler enhancement is accounted for. It may be significant that the maximum luminosity of extended radio sources, $\sim 10^{46}$ ergs s^{-1} (Miley 1980), is roughly equal to the power that would be required in a beamed component of a bright blazar. This supports the idea that the same jet is responsible for both phenomena. The scenario of a polarized, low-luminosity source that is relativistically beamed is quite different from that envisioned by Stockman (1978). If the polarized emission were *isotropic*, then at its brightest it would have a total luminosity equal to that of the brightest known QSOs ($\sim 10^{48}$ ergs s^{-1}). Unpolarized objects could then be explained as objects whose light was produced initially in the same way but was then depolarized and stabilized by scattering.

The situation for the BL Lac objects is not clear. The many similarities in the observed properties suggest we are seeing something closely related to the polarized quasars but without the strong emission lines and associated unpolarized continuum. In terms of the relativistic beam models, it may be that in the strongest BL Lac's, like AO 0235+164 or OJ 287, we are viewing directly into a similar beam, and the weaker ones are the same thing viewed from an oblique angle. Alternatively, or in addition, we could be viewing a different population of weaker objects head on.

Direct evidence that our view is sometimes oblique is provided by the two objects that lie at the center of double-lobe radio sources, 1400+162 and 3C 390.3. It is hard to guess what the angle between the lobe axis and the line of sight might be, but at least in 3C 390.3, which has an unusually small ratio of the lobe size to separation (Harris 1972), it would seem that it cannot be small. The fact that in both these objects the polarization is stable in angle and is aligned with the radio axis suggests that the property of stable position angle in many of the fainter BL Lac objects (Section III) may be related to their being viewed obliquely.

In a relativistic jet theory the misdirected jets that we argue must also be present in radio-quiet quasars could be emitting at the same strength of radio emission and polarized optical radiation that we see in BL Lac objects, and would pass unnoticed. The luminosity of the weaker BL Lacs of 10^{31} ergs s^{-1} Hz^{-1} would be detected at less than 1 mJy for $z > 0.3$, and the optical polarization could easily be diluted to less than 1% by the unpolarized continuum associated with the emission lines. It is tempting to speculate that the weakly aligned polarization found in double-lobe radio quasars could be of this type. If this were correct it would imply that the optical flux is not extremely dependent on angle, and that relatively low values of γ (<2) are typical.

A case that at least some BL Lac objects are viewed at small angle to the jet axis can be made if we identify the steep-spectrum extended component in some objects as radio doubles seen end on (M. J. Rees, private communication). This idea can be developed as follows. Three of the objects in Table 1 at $z < 0.1$ show such a component to their radio emission, namely 3C 84, 3C 371, and PKS 0521−36. A lower limit to the typical angle of view of these objects can be derived if we assume they emit the steep-spectrum component isotropically. The space density of all radio sources of similar luminosity is some 30 times greater than that of these objects. Thus if all radio galaxies would show polarized nuclei when viewed end on, then we deduce the typical angle of view for the three objects is ~0.25. Larger angles will be needed if only a subset of radio galaxies are involved. If the strong extended component of PKS 0521 − 36 and 3C 371 were shown to be a halo like 3C 84 and not two lobes closely spaced by foreshortening, this would be strong evidence that these objects were being viewed at close to random angles, since halo sources are rare. On the other hand, if these two sources showed core-jet structure it could indicate that even the low-frequency component is relativistically beamed. Such beaming is required for the strong, steep-spectrum emission of the classic OVV quasars in the statistical analysis of Scheuer & Readhead (1979).

One prediction made by relativistic beam models is that the fluctuation time scale for relativistic jets seen head on will be more rapid than when viewed obliquely. The fact that the time scale of one day for the extremely bright source B2 1308 + 326 is not markedly different from much fainter sources is given as an argument against relativistic beams by Moore et al. (1980). However, we note that rather modest values of γ of 2 or 3 give extremely large intensity enhancement in the forward over oblique directions, while causing modest changes in time scale. Given our present knowledge of variability, such changes could easily have escaped notice. In fact B2 1308 + 326 has as large an amplitude variation from day to day (allowing a factor two for cosmological redshift) as any known object. A good test of these ideas would be a comparison of the time scales for changes in the polarization in the most luminous sources with the time scales in sources where a restricted range of position angle or the presence of a double radio source indicates an oblique view. In general, these latter sources are not as well studied as the wildly varying ones.

VII *Conclusions*

The use of optical and infrared polarimetry to study active extragalactic objects is a powerful method to obtain information about the innermost core of the central engines. As Rees (1978a) has stressed, the spatial scale of 10^{15} cm indicated by the variability of the polarized optical emission is a thousand times smaller than the compact radio structures of $\sim 10^{18}$ cm studied by VLBI. Until recently there were few detailed predictions that could drive specific polarimetric tests of quasar models. The development of black hole accretion theories and relativistic jet models now suggests a wide range of studies.

One general study will be a quantitative analysis of the statistics of occurrence of polarization and large optical variability in objects ranging from the ellipticals with weak compact sources to the bright quasars. Correlating the polarization with on the one hand properties known to be isotropic such as galaxy luminosity, emission line strengths, and symmetric extended radio emission, and on the other with compact flat-spectra, low-frequency variability, and so on, should give a much better understanding of the role of relativistic beaming. Another area that should also be rewarding will be synoptic studies of the rapid variations in polarization and flux, ideally measurements correlated in the X-ray, infrared, and optical spectra. Because the time scales are around a day, coordinated measurements from satellites or several observatories around the world are needed. With modern instrumentation, modest telescopes of ~ 1 m aperture are adequate for this work. These data should shed much light on the primary mechanisms for energy release deep in the central powerhouse.

Additional studies of weakly polarized or dusty nuclei would be extremely valuable. For the majority of QSOs, high quality, multicolor polarimetry and spectropolarimetry should discriminate between scattering and nonthermal origins of the observed polarization. In the Seyfert nuclei, imaging polarimetry from space and spectropolarimetry similar in quality to the beautiful spectrum of NGC 4151 obtained by Schmidt & Miller (1979) could establish the spatial and kinematic relationship of the dust clouds within the narrow and broad line emission regions. The general polarization surveys should be extended into the ultraviolet to study the characteristics of nuclear dust and to smaller apertures to search for dust or nonthermal sources in active and normal galaxies.

ACKNOWLEDGMENTS

We are grateful to many colleagues for letting us have preprints in advance of publication, and especially to Richard Moore for preparing the two tables. This review has benefitted also from the help of Drs. Jones, Miley, Moore, Puschell, Rieke, Rudnick, Scheuer, Stein, Tapia, and Wardle, who pointed out errors and suggested improvements in the first draft. This work is supported by the NSF under grant AST-78-22714.

Literature Cited

Aller, H. D., Ledden, J. E. 1978. *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe, p. 53. Univ. Pittsburgh Press

Altschuler, D. R. Wardle, J. F. C. 1976. *Mem. R. Astron. Soc.* 82:1

Angel, J. R. P., Stockman, H. S., Woolf, N. J., Beaver, E. A., Martin, P. G. 1976. *Ap. J. Lett.* 206:L5

Angel, J. R. P. et al. 1978. *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe, p. 117. Univ. Pittsburgh Press

Angel, J. R. P., Moore, R. L. 1980. *Ann. NY Acad. Sci.* 336:55

Appenzeller, I., Hiltner, W. A. 1967. *Ap. J. Lett.* 149:L17

Baade, W. 1956. *Ap. J.* 123:550

Babadzhanyants, M. K., Hagen-Thorn, V. A., Ljutyi, V. M. 1972. *Astrophysics* 8:300

Babadzhanyants, M. K., Hagen-Thorn, V. A., Semenova, E. V. 1972. *Astron. Tsirk.* 701:1

Babadzhanyants, M. K., Hagen-Thorn, V. A. 1975. *Astrophysics* 11:259

Bailey, J. A., Pooley, G. G. 1968. *MNRAS* 138:51

Baldwin, J. A. 1975. *Ap. J.* 201:26

Baldwin, J. A., Wampler, E. J., Burbidge, E. M., O'Dell, S. L., Smith, H. E., Hazard, C., Nordsieck, K. H., Pooley, G., Stein, W. A. 1977. *Ap. J.* 215:408

Bingham, R. G., McMullan, D., Pallister, W. S., White, C., Axon, D. J., Scarrott, S. M. 1976. *Nature* 259:463

Blandford, R. D., Rees, M. J. 1974. *MNRAS* 169:395

Blandford, R. D. 1976. *MNRAS* 176:465

Blandford, R. D., Rees, M. J. 1978. *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe, p. 328. Univ. Pittsburgh Press

Blandford, R. D., Königl, A. 1979. *Ap. J.* 232:34

Bolton, J. G., Shimmins, A. J., Wall, J. V. 1975. *Aust. J. Phys. Suppl.* 34:1

Brandie, G. W., Bridle, A. H. 1974. *Astron. J.* 79:903

Bridle, A. H., Davis, M. M., Fomalont, E. B., Lequeux, J. 1972. *Astron. J.* 77:405

Bridle, A. H., Fomalont, E. B. 1974. *Astron. J.* 79:1000

Broderick, J. J., Kellermann, K. I., Shaffer, D. B., Jauncey, D. L. 1972. *Ap. J.* 172:299

Burbidge, E. M. 1968. *Ap. J. Lett.* 152:L111

Burbidge, G. R., Jones, T. W., O'Dell, S. L. 1974. *Ap. J.* 193:43

Burbidge, G. R., Crowne, A. H., Smith, H. E. 1977. *Ap. J. Suppl.* 33:113

Cannon, R. D., Penston, M. V., Brett, R. A. 1971. *MNRAS* 152:79

Capps, R. W., Knacke, R. F. 1978. *Astrophys. Lett.* 19:113

Carswell, R. F., Strittmatter, P. A., Disney, M. J., Hoskins, D. G., Murdock, H. S. 1973. *Nature* 246:89

Carswell, R. F., Strittmatter, P. A., Williams, R. E., Kinman, T. D., Serkowski, K. 1974. *Ap. J. Lett.* 190:L101

Charles, P., Thorstensen, J., Bowyer, S. 1979. *Nature* 281:285

Cohen, M. H., Cannon, W., Purcell, G. H., Shaffer, D. B., Broderick, J. J., Kellermann, K. I., Jauncey, D. L. 1971. *Ap. J.* 170:207

Cohen, M. H., Pearson, T. J., Readhead, A. C. S., Seielstad, G. A., Simon, R. S., Walker, R. C. 1979. *Ap. J.* 231:293

Colgate, S. A., Petschek, A. G. 1978. *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe, p. 345. Univ. Pittsburgh Press

Colla, G., Fanti, C., Fanti, R., Ficarra, A., Formiggini, L., Gandolfi, E., Grueff, G., Lari, C., Padrielli, L., Roffi, G., Tomasi, P., Vigotti, M. 1970. *Astron. Astrophys. Suppl.* 1:281

Colla, G., Fanti, C., Fanti, R., Ficarra, A., Formiggini, L., Gandolfi, E., Lari, C., Marano, B., Padrielli, L., Tomasi, P. 1972. *Astron. Astrophys. Suppl.* 7:1

Colla, G., Fanti, C., Fanti, R., Ficarra, A., Formiggini, L., Gandolfi, E., Gioia, I., Lari, C., Marano, B., Padrielli, L., Tomasi, P. 1973. *Astron. Astrophys. Suppl.* 11:291

Condon, J. J., Jauncey, D. L. 1974a. *Astron. J.* 79:437

Condon, J. J., Jauncey, D. L. 1974b. *Astron. J.* 79:1220

Condon, J. J., Dennison, B. 1978. *Ap. J.* 224:835

Condon, J. J. 1978. *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe, p. 21. Univ. Pittsburgh Press

Condon, J. J., Ledden, J. E., O'Dell, S. L., Dennison, B. 1979. *Astron. J.* 84:1

Conway, R. G., Stannard, D. 1972. *MNRAS* 160:31P

Conway, R. G., Haves, P., Kronberg, P. P., Stannard, D., Vallee, J. P., Wardle, J. F. C. 1974. *MNRAS* 168:137

Cooke, B. A., Ricketts, M. J., Maccacaro, T., Pye, J. P., Elvis, M., Watson, M. G., Griffiths, R. E., Pounds, K. A., McHardy, I., Maccagni, D., Seward, F. D., Page, C. G., Turner, J. J. L. 1978. *MNRAS* 182:489

Cotton, W. D., Counselman, C. C., Geller, R. B., Shapiro, I. I., Wittels, J. J., Hinteregger, H. F., Knight, C. A., Rogers, A. E. E., Whitney, A. R., Clark, T. A. 1979. *Ap. J. Lett.* 229:L115

Craine, E. R., Duerr, R., Tapia, S. 1978. *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe, p. 99. Univ. Pittsburgh Press

Danziger, I. J., Fosbury, R. A. E., Goss, W. M., Ekers, R. D. 1979. *MNRAS* 188:415

Davidson, K., Netzer, H. 1979. *Rev. Mod. Phys.* 51:715

Davis, R. J., Stannard, D., Conway, R. G. 1977. *Nature* 267:596

deBruyn, A. G., Willis, A. G. 1974. *Astron. Astrophys.* 33:351

Dent, W. A. 1965. *Science* 148:1458

de Vaucouleurs, G., Nieto, J.-L. 1979. *Bull. Am. Astron. Soc.* 10:629

Dibaj, E. A., Shakhovskoy, N. M. 1966. *Astron. Tsirk.* 375:1

Dombrovsky, V. A., Hagen-Thorn, V. A. 1968. *Astrophysics* 4:163

Dombrovsky, V. A., Babadzhanyants, M. K., Hagen-Thorn, V. A., Houtkevich, S. M. 1971. *Astrophysics* 7:246

Dower, R. G., Griffiths, R. E., Bradt, H. V., Doxsey, R. E., Johnston, M. D. 1980. *Ap. J.* 235:355

Dyck, H. M., Kinman, T. D., Lockwood, G. W., Landolt, A. U. 1971. *Nature* 234:71

Eachus, L. J., Liller, W. 1975. *Ap. J. Lett.* 200:L61

Eardley, D. M., Lightman, A. P., Payne, D. G., Shapiro, S. L. 1978. *Ap. J.* 224:53

Efimov, Y. S., Shakhovskoy, N. M. 1972. *Izv. Krymskoj Astrofiz. Obs.* 46:3
Ekers, J. A. 1969. *Aust. J. Phys. Suppl.* 7:1
Elliot, J. L., Shapiro, S. L. 1974. *Ap. J. Lett.* 192:L3
Elsmore, B., Mackay, C. D. 1969. *MNRAS* 146:361
Elvius, A. 1968. *Lowell Obs. Bull. No. 142* 7:5
Elvius, A. 1972. *Interstellar Dust and Related Topics*, ed. J. M. Greenberg, H. C. van de Hulst. Dordrecht: Reidel
Elvius, A. 1978. *Astron. Astrophys.* 65:233
Fomalont, E. B. 1967. *Ap. J. Suppl.* 15:203
Fomalont, E. B., Moffet, A. T. 1971. *Astron. J.* 76:5
Gardner, F. F., Whiteoak, J. B., Morris, D. 1975. *Aust. J. Phys. Suppl.* 35:1
Gaskell, C. M. 1978. *Bull. Am. Astron. Soc.* 10:662
Geller, M. J., Turner, E. L., Bruno, M. S. 1979. *Ap. J. Lett.* 230:L141
Goldsmith, D. W., Kinman, T. D. 1965. *Ap. J.* 142:1693
Gottlieb, E. W., Liller, W. 1976. *IAU Circ. No. 2939*
Gower, J. F. R., Scott, P. F., Wills, D. 1967. *Mem. R. Astron. Soc.* 71:49
Grandi, S. A., Tifft, W. G. 1974. *Publ. Astron. Soc. Pac.* 86:873
Griffiths, R. E., Tapia, S., Briel, U., Chaisson, L. 1979. Preprint
Hagen-Thorn, V. A. 1972. *Astron. Tsirk.* 714:5
Hagen-Thorn, V. A. 1974. *Astrophysics* 10:79
Harris, A. 1972. *MNRAS* 158:1
Hazard, C., Gulkis, S., Sutton, J. 1968. *Ap. J.* 154:413
Heeschen, D. S. 1973. *Ap. J. Lett.* 179:L93
Hiltner, W. A. 1959. *Ap. J.* 130:340
Hine, R. G., Scheuer, P. A. G. 1980. Preprint
Hobbs, R. W., Dent, W. A. 1977. *Astron. J.* 82:257
Hoyle, F., Burbidge, G. R., Sargent, W. L. W. 1966. *Nature* 209:751
Jauncey, D. L., Bare, C. C., Clark, B. G., Kellermann, K. I., Cohen, M. H. 1970. *Ap. J.* 160:337
Jones, T. W., O'Dell, S. L., Stein, W. A. 1974. *Ap. J.* 192:261
Jones, T. W., Leung, C. M., Gould, R. J., Stein, W. A. 1977. *Ap. J.* 212:52
Jones, T. W., O'Dell, S. L. 1977a. *Ap. J.* 215:236
Jones, T. W., O'Dell, S. L. 1977b. *Astron. Astrophys.* 61:291
Jones, T. W., Rudnick, L. 1980. Private communication
Katz, J. I. 1976. *Ap. J.* 206:910
Kellermann, K. I., Pauliny-Toth, I. I. K. 1968. *Ann. Rev. Astron. Astrophys.* 6:417
Kellermann, K. I., Pauliny-Toth, I. I. K. 1969. *Ap. J. Lett.* 155:L71
Kellermann, K. I., Pauliny-Toth, I. I. K., Williams, P. J. S. 1969. *Ap. J.* 157:1
Kellermann, K. I., Clark, B. G., Jauncey, D. L., Cohen, M. H., Shaffer, D. B., Moffet, A. T., Gulkis, S. 1970. *Ap. J.* 161:803
Kellermann, K. I., Pauliny-Toth, I. I. K. 1971. *Astrophys. Lett.* 8:153
Kellermann, K. I., Jauncey, D. L., Cohen, M. H., Shaffer, B. B., Clark, B. G., Broderick, J., Rönnäng, B., Rydbeck, O. E. H., Matveyenko, L., Moiseyev, I., Vitkevich, V. V., Cooper, B. F. C., Batchelor, R. 1971. *Ap. J.* 169:1
Kellermann, K. I., Shaffer, D. B., Purcell, G. H., Pauliny-Toth, I. I. K., Preuss, E. Witzel, A., Graham, D., Schilizzi, R. T., Cohen, M. H., Moffet, A. T., Romney, J. D., Niell, A. E. 1977. *Ap. J.* 211:658
Kellermann, K. I. 1978. *Phys. Scripta* 17:257
Kemp, J. C., Wolstencroft, R. D., Swedlund, J. B. 1972. *Ap. J. Lett.* 173:L113
Kemp, J. C., Rieke, G. H., Lebofsky, M. J., Coyne, G. V. 1977. *Ap. J. Lett.* 215:L107
Khachikian, E. Y., Weedman, D. W. 1974. *Ap. J. Lett.* 189:L99
Kikuchi, S., Mikami, Y., Konno, M., Inoue, M. 1976. *Publ. Astron. Soc. Jpn.* 28:117
Kinman, T. D., Lamla, E., Wirtanen, C. A. 1966. *Ap. J.* 146:964
Kinman, T. D. 1967. *Ap. J. Lett.* 148:L53
Kinman, T. D., Lamla, E., Ciurla, T., Harlan, E., Wirtanen, C. A. 1968. *Ap. J.* 152:357
Kinman, T. D., Conklin, E. K. 1971. *Astrophys. Lett.* 9:147
Kinman, T. D. 1973. *Ap. J. Lett.* 179:L97
Kinman, T. D., Wardle, J. F. C., Conklin, E. K., Andrew, B. H., Harvey, G. A., Macleod, J. M., Medd, W. J. 1974. *Ap. J.* 79:349
Kinman, T. D. 1976. *Ap. J.* 205:1
Kinman, T. D. 1977. *Nature* 267:798
Kinzer, R. L. 1978. *Bull. Am. Astron. Soc.* 10:503
Knacke, R. F., Capps, R. W. 1974. *Ap. J. Lett.* 192:L19
Knacke, R. F., Capps, R. W., Johns, M. 1976. *Ap. J. Lett.* 210:L69
Knacke, R. F., Capps, R. W., Johns, M. 1979. *Nature* 280:215
Kojoian, G., Stramek, R. A., Dickinson, D. F., Tovmassian, H., Purton, C. R. 1976. *Ap. J.* 203:323
Korchakov, A. A., Syrovatskii, S. I. 1962. *Sov. Astron.-AJ* 5:678
Kruszewski, A. 1968. *Astron. J.* 73:852
Kruszewski, A. 1977. *Acta Astron.* 27:319
Landstreet, J. D., Angel, J. R. P. 1972. *Ap. J. Lett.* 174:L127
Lebofsky, M. J., Rieke, G. H., Kemp, J. C. 1978. *Ap. J.* 222:95
Liller, W. 1969. *Ap. J.* 155:1113
Lovelace, R. V. E. 1976. *Nature* 262:649

Lynden-Bell, D., Pringle, J. E. 1974. *MNRAS* 168:603

Lynds, C. R. 1967. *Ap. J.* 147:396

MacDonald, G. H., Kenderdine, S., Neville, A. C. 1968. *MNRAS* 138:259

Mackay, C. D. 1969. *MNRAS* 145:31

Mackay, C. D. 1971. *MNRAS* 154:209

Macleod, J. M., Andrew, B. H. 1968. *Astrophys. Lett.* 1:243

Marscher, A. P. 1980. *Ap. J.* 235:386

Marshall, F. E., Mushotzky, R. F., Boldt, E. A., Holt, S. S., Rothschild, R. E., Serlemitsos, P. J. 1978. *Nature* 275:624

Martin, P. G., Angel, J. R. P., Maza, J. 1976. *Ap. J. Lett.* 209:L21

Martin, P. G. 1979. *Cosmic Dust.* Oxford: Clarendon

Maza, J., Martin, P. G., Angel, J. R. P. 1978. *Ap. J.* 224:368

Maza, J. 1979. *Polarization of Seyfert Galaxies and Related Objects.* PhD. thesis. Univ. Toronto, Toronto

Maza, J., Martin, P. G., Angel, J. R. P. 1980. In preparation

McGimsey, B. Q., Smith, A. G., Scott, R. L., Leacock, R. J., Edwards, P. L., Hackney, R. L., Hackney, K. R. 1975. *Ap. J.* 80:895

Miley, G. K., Perola, G. C. 1975. *Astron. Astrophys.* 45:223

Miley, G. K. 1980. *Ann. Rev. Astron. Astrophys.* 18:165

Miller, J. S. 1975. *Ap. J. Lett.* 200:L55

Miller, J. S. 1978. *Comments Astrophys.* 7:175

Miller, J. S., French, H. B. 1978. *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe, p. 228. Univ. Pittsburgh Press

Miller, J. S., French, H. B., Hawley, S. A. 1978. *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe, p. 176. Univ. Pittsburgh Press

Mills, B. Y., Slee, O. B., Hill, E. R. 1960. *Aust. J. Phys.* 13:676

Mills, B. Y., Little, A. G. 1970. *Astrophys. Lett.* 6:197

Moore, R. L., Angel, J. R. P., Rieke, G. H., Lebofsky, M. J., Wisniewski, W. Z., Mufson, S. L., Vrba, F. J., Miller, H. R., McGimsey, B. Q., Williamson, R. M. 1980. *Ap. J.* 235:717

Moore, R. L., Stockman, H. S. 1980. *Ap. J.* In press

Moore, R. L., Stockman, H. S., Angel, J. R. P. 1980. In preparation

Munro, R. E. B. 1972. *Aust. J. Phys. Suppl.* 22:1

Mushotzky, R. F., Boldt, E. A., Holt, S. S., Pravdo, S. H., Serlemitsos, P. J., Swank, J. H., Rothschild, R. H. 1978. *Ap. J. Lett.* 226:L65

Mushotzky, R. F., Marshall, F. E., Boldt, E. A., Holt, S. S., Serlemitsos, P. J. 1980. *Ap. J.* 235:361

Neugebauer, G., Oke, J. B., Becklin, E. E., Matthews, K. 1979. *Ap. J.* 230:79

Noerdlinger, P. D. 1978. *Phys. Rev. Lett.* 41:135

Nordsieck, K. H. 1972. *Astrophys. Lett.* 12:69

Nordsieck, K. H. 1976. *Ap. J.* 209:653

O'Dell, S. L., Puschell, J. J., Stein, W. A., Owen, F., Porcas, R. W., Mufson, S., Moffett, T. J., Ulrich, M.-H. 1978. *Ap. J.* 224:22

Oke, J. B. 1966. *Ap. J.* 145:668

Oke, J. B., Sargent, W. L. W., Neugebauer, G., Becklin, E. E. 1967. *Ap. J. Lett.* 150:L173

Oke, J. B., Neugebauer, G., Becklin, E. E. 1970. *Ap. J.* 159:341

Osterbrock, D. E., Miller, J. S. 1975. *Ap. J.* 197:535

Osterbrock, D. E., Koski, A. T., Phillips, M. M. 1976. *Ap. J.* 206:898

Owen, F. N., Mufson, S. L. 1977. *Astron. J.* 82:776

Owen, F. N., Porcas, R. W., Mufson, S. L., Moffett, T. J. 1978. *Astron. J.* 83:685

Owen, F., Spangler, S. R., Cotton, W. 1980. Preprint

Pacini, F., Salvati, M. 1978. *Ap. J. Lett.* 225:L99

Pauliny-Toth, I. I. K., Kellermann, K. I. 1972. *Astron. J.* 77:797

Pauliny-Toth, I. I. K., Kellermann, K. I., Davis, M. M., Fomalont, E. B., Shaffer, D. B. 1972. *Astron. J.* 77:265

Pauliny-Toth, I. I. K., Witzel, A., Preuss, E., Kuhr, H., Kellermann, K. I., Fomalont, E. B., Davis, M. M. 1978. *Astron. J.* 83:451

Penston, M. V., Penston, M. J. 1973. *MNRAS* 162:109

Petschek, A. G., Colgate, S. A., Colvin, J. D. 1976. *Ap. J.* 209:356

Pica, A. J. 1977. *Astron. J.* 82:935

Pilkington, J. D. H., Scott, J. F. 1965. *Mem. R. Astron. Soc.* 69:183

Pollock, J. T., Pica, A. J., Smith, A. G., Leacock, R. J., Edwards, P. L., Scott, R. L. 1979. *Astron. J.* 84:1658

Porcas, R. W., Treverton, A. M., Wilkinson, A. 1974. *MNRAS* 167:41P

Puschell, J. J., Stein, W. A., Jones, T. W., Warner, J. W., Owen, F., Rudnick, L., Aller, H., Hodge, P. 1979. *Ap. J. Lett.* 227:L11

Puschell, J. J., Stein, W. A. 1980. Preprint

Puschell, J. J. 1980. Private communication

Readhead, A. C. S., Cohen, M. H., Blandford, R. D. 1978. *Nature* 272:131

Readhead, A. C. S., Cohen, M. H., Pearson, T. J., Wilkinson, P. N. 1978. *Nature* 276:768

Readhead, A. C. S., Pearson, T. J., Cohen, M. H., Ewing, M. S., Moffet, A. T. 1979. *Ap. J.* 231:299

Rees, M. J., Sciama, D. W. 1965. *Nature* 207:738
Rees, M. J., Simon, M. 1968. *Ap. J. Lett.* 152:L145
Rees, M. J. 1978a. *Phys. Scripta* 17:193
Rees, M. J. 1978b. *Nature* 275:516
Richstone, D., Schmidt, M. 1980. *Ap. J.* 235:361
Riegler, G. R., Agrawal, P. C., Mushotzky, R. F. 1979. Preprint
Rieke, G. H., Grasdalen, G. L., Kinman, T. D., Hinzen, P., Wills, B. J., Wills, D. 1976. *Nature* 260:754
Rieke, G. H., Lebofsky, M. J., Kemp, J. C., Coyne, G. V., Tapia, S. 1977. *Ap. J. Lett.* 218:L37
Rieke, G. H., Lebofsky, M. J. 1979. *Ann. Rev. Astron. Astrophys.* 17:477
Rudnick, L., Owens, F. N., Jones, T. W., Puschell, J. J., Stein, W. A. 1978. *Ap. J. Lett.* 225:L5
Sandage, A. 1967. *Ap. J. Lett.* 150:L177
Sargent, W. L. W., Young, P. J., Boksenberg, A., Shortridge, K., Lynds, C. R., Hartwick, F. D. A. 1978. *Ap. J.* 221:731
Scheuer, P. A. G., Readhead, A. C. S. 1979. *Nature* 277:182
Schmidt, G. D., Angel, J. R. P., Cromwell, R. H. 1976. *Ap. J.* 206:888
Schmidt, G. D., Peterson, B. M., Beaver, E. A. 1978. *Ap. J. Lett.* 220:L31
Schmidt, G. D., Miller, J. S. 1979. Preprint
Schmidt, M. 1974. *Ap. J.* 193:505
Schmidt, M. 1978. *Phys. Scripta* 17:135
Schmitt, J. L. 1968. *Nature* 218:663
Schwartz, D. A., Doxsey, R. E., Griffiths, R. E., Johnston, M. D., Schwarz, J. 1979. *Ap. J. Lett.* 229:L53
Sciama, D. W., Rees, M. J. 1967. *Nature* 216:147
Seilestad, G. A., Cohen, M. H., Linfield, R. P., Moffet, A. T., Romney, J. D., Schilizzi, R. T. 1979. *Ap. J.* 229:53
Serkowski, K., Tapia, S. 1975. *Bull. Am. Astron. Soc.* 7:499
Shaffer, D. B. 1978. *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe, p. 68. Univ. Pittsburgh Press
Shields, G. A. 1978. *Nature* 272:706
Shimmins, A. J., Manchester, R. N., Harris, B. J. 1969. *Aust. J. Phys. Suppl.* 8:1
Shimmins, A. J., Bolton, J. G. 1972. *Aust. J. Phys. Suppl.* 23:1
Shimmins, A. J., Bolton, J. G. 1974. *Aust. J. Phys. Suppl.* 32:1
Shimmins, A. J., Bolton, J. G., Wall, J. V. 1974. *Aust. J. Phys. Suppl.* 34:63
Shklovsky, I. S. 1955. *IAU Symp. No. 4*, p. 205
Slee, O. B. 1977. *Aust. J. Phys. Suppl.* 43:1
Smith, H. E., Spinrad, H., Smith, E. O. 1976. *Publ. Astron. Soc. Pac.* 88:621
Smith, H. E., Burbidge, E. M., Baldwin, J. A., Tohline, J. E., Wampler, E. J., Hazard, C., Murdoch, H. S. 1977. *Ap. J.* 215:427
Smith, H. E. 1978. *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe, p. 211. Univ. Pittsburgh Press
Stein, W. A., O'Dell, S. L., Strittmatter, P. A. 1976. *Ann. Rev. Astron. Astrophys.* 14:173
Stockman, H. S., Angel, J. R. P., Beaver, E. A. 1976. *Bull. Am. Astron. Soc.* 8:495
Stockman, H. S., Angel, J. R. P. 1978. *Ap. J. Lett.* 220:L67
Stockman, H. S., Angel, J. R. P., Hier, R. 1978. *Bull. Am. Astron. Soc.* 10:689
Stockman, H. S. 1978. *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe, p. 149. Univ. Pittsburgh Press
Stockman, H. S., Angel, J. R. P., Miley, G. K. 1979. *Ap. J. Lett.* 227:L55
Strittmatter, P. A., Serkowski, K., Carswell, R., Stein, W. A., Merrill, K. M., Burbidge, E. M. 1972. *Ap. J. Lett.* 175:L7
Strittmatter, P. A., Carswell, R. F., Gilbert, G., Burbidge, E. M. 1974. *Ap. J.* 190:509
Sulentic, J. W., Arp, H., Lorre, J. 1979. *Ap. J.* 233:44
Sutton, J. M., Davies, I. M., Little, A. G., Murdoch, H. S. 1974. *Aust. J. Phys. Suppl.* 33:1
Tananbaum, H., Avni, Y., Branduardi, G., Elvis, M., Fabbiano, G., Feigelson, E., Giacconi, R., Henry, J. P., Pye, J. P., Soltan, A., Zamorani, G. 1980. *Ap. J. Lett.* 234:L9
Tapia, S., Craine, E. R., Johnson, K. 1976. *Ap. J.* 203:291
Tapia, S., Craine, E. R., Gearhart, M. R., Pacht, E., Kraus, J. 1977. *Ap. J. Lett.* 215:L71
Thompson, I., Landstreet, J. D., Angel, J. R. P., Stockman, H. S., Woolf, N. J., Martin, P. G., Maza, J., Beaver, E. A. 1979. *Ap. J.* 229:909
Thompson, I., Landstreet, J. D., Stockman, H. S., Angel, J. R. P., Beaver, E. A. 1980. *MNRAS*. In press
Turland, B. D. 1975. *MNRAS* 170:281
Turnshek, D. A., Weymann, R. J., Liebert, J. W., Williams, R. E., Strittmatter, P. A. 1979. Preprint
Ulrich, M. H., Kinman, T. D., Lynds, C. R., Rieke, G. H., Ekers, R. D. 1975. *Ap. J.* 198:261
Ulrich, M. H. 1978. *Ap. J. Lett.* 222:L3
Usher, P. D., Kolpanen, D. R., Pollock, J. T. 1974. *Nature* 252:365
Usher, P. D. 1975. *Ap. J. Lett.* 198:L57
Visvanathan, N. 1967. *Ap. J. Lett.* 150:L149
Visvanathan, N. 1968. *Ap. J. Lett.* 153:L19
Visvanathan, N., Oke, J. B. 1968. *Ap. J. Lett.* 152:L165.
Visvanathan, N. 1969. *Ap. J. Lett.* 155:L133
Visvanathan, N. 1973a. *Ap. J.* 179:1
Visvanathan, N. 1973b. *Ap. J.* 185:145
Visvanathan, N. 1974. *Planets, Stars and*

Nebulae, ed. T. Gehrels. Tucson: Univ. Arizona Press
Walker, M. F. 1964. *Astron. J.* 69:682
Walker, M. F. 1968. *Ap. J.* 151:71
Wall, J. V., Shimmins, A. J., Merkelijn, J. K. 1971. *Aust. J. Phys. Suppl.* 19:1
Wall, J. V. 1972. *Aust. J. Phys. Suppl.* 24:1
Wall, J. V., Wright, A. E., Bolton, J. G. 1976. *Aust. J. Phys. Suppl.* 39:1
Wampler, E. J. 1967. *Ap. J.* 147:1
Wampler, E. J. 1971. *Ap. J.* 164:1
Wardle, J. F. C. 1971. *Astrophys. Lett.* 8:183
Wardle, J. F. C. 1977. *Nature* 269:563
Wardle, J. F. C. 1978. *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe, p. 39. Univ. Pittsburgh Press
Weiler, K. W., Johnston, K. J. 1979. Preprint
Whiteoak, J. B. 1966. *Z. Astrophys.* 64:181
Williams, P. J. S., Kenderdine, S., Baldwin, J. E. 1966. *Mem. R. Astron. Soc.* 70:53
Williams, W. L., Rich, A., Kupferman, P. N., Ionson, J. A., Hiltner, W. A. 1972. *Ap. J. Lett.* 174:L63
Wills, D., Wills, B. J. 1974. *Ap. J.* 190:271
Wills, D., Wills, B. J. 1976. *Ap. J. Suppl.* 31:143
Witzel, A., Pauliny-Toth, I. I. K., Geldzahler, B. J., Kellermann, K. I. 1978. *Astron. J.* 83:475
Woltjer, L. 1966. *Ap. J. Lett.* 146:597
Young, P. J., Westphal, J. A., Kristian, J., Wilson, C. P., Landauer, F. P. 1978. *Ap. J.* 221:721
Zotov, N. V., Tapia, S. 1979. *Ap. J. Lett.* 229:L5
Zwicky, F. 1966. *Ap. J.* 143:192