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2.7-GHz OBSERVATIONS OF FOUR RADIO POLARIZATION ROTATORS

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ABSTRACT

We present 2.7-GHz measurements of the flux density and linear polarization of four quasi-stellar objects: 0048 − 097, 0607 − 157, 0727 − 115, and 2200 + 420 (BL Lac) obtained over an 8-yr period. The broadband (2.7–90 GHz) spectral evolution of selected outbursts is also presented. The polarization variations at 2.7 GHz are smaller in amplitude than those observed at higher frequencies. The large changes in position angle observed at 8 GHz in these sources are not seen at 2.7 GHz; and the low-frequency curvature in the radio spectra suggests that the rotations occur within a region which becomes opaque near 2.7 GHz.

I. INTRODUCTION

One of the most interesting phenomena observed in some compact radio sources is apparent rotations in the linear polarization position angle. The first observed linear rotation in position angle was in the BL Lacertae type quasi-stellar object 0235 + 164 (Ledden and Aller 1979). Since then rotations have been reported in seven other sources: 0048 − 097, 0133 + 476, 0235 + 164, 1510 − 089, and 1749 + 096, Altschuler (1980); 0607 − 157 and 0727 − 115, Aller, Aller, and Hodge (1981, AAH); and 2200 + 420 (BL Lac), Aller, Hodge, and Aller (1981, AHA).

In those cases where multifrequency observations are available, the rotation rate is the same at all frequencies where the rotation is observed. In some sources there is an apparent low-frequency cutoff to the rotation. The rotation in 0727 − 115 and 2200 + 420 is seen at 4.8, 8.0, and 14.5 GHz (AHA) but not at 2.7 GHz (this paper); in 0607 − 157 at 8.0 (AAH) but not at 2.7 GHz (this paper); and also at 8.0 GHz but not at 2.7 GHz in 0048 − 097 (Altschuler 1980 and this paper), and 0133 + 476, 0235 + 164, and 1510 − 089 (Altschuler 1980).

Three possibilities for the lack of low-frequency rotation are: (1) the existence of a polarized steep spectrum "masking" component which dominates the polarization at the lower frequencies (e.g., Altschuler 1980); (2) synchrotron self-absorption which prevents us from seeing deep into the core where the rotation is presumably occurring. [Thermal absorption in these sources can be ruled out by the lack of Faraday rotation (e.g., Wardle 1977; Jones and O'Dell 1977).]; and (3) a low-frequency cutoff intrinsic to the rotation mechanism.

A rotation in position angle of 90° will occur near an opacity of ~0.5 as an initially opaque homogeneous synchrotron component becomes transparent (Pacholczyk and Swihart 1967; Aller 1970; Takarada 1970; Pacholczyk 1977). This rotation is accompanied by a rapid decline in the percent polarization to zero followed by an increase as the opacity decreases further. This mechanism may be important at "low" frequencies such as 2.7 GHz where the continuum spectral evolution suggests that opacity effects can be significant [e.g., in OJ 287 (Aller and Ledden 1978) and 1308 + 326 (O'Dea, Dent, and Balonek 1983)]. However, this mechanism cannot account for the observed rotations which are much greater than 90°.

In this paper we present 2.7-GHz measurements of the flux density and linear polarization in the four rotators 0048 − 097, 0607 − 157, 0727 − 115, and 2200 + 420 obtained over an 8-yr period. Broadband (2.7–90 GHz) spectra of these sources are also presented. We discuss the spectral evolution of selected outbursts, and the polarization variations and in particular the lack of low-frequency rotation in these sources. Polarization variations in 0133 + 476 are discussed by Dent, O'Dea, and Kinzel (1982).

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TABLE I. 2.7-GHz flux density and linear polarization measurements.

DATE	S_T (Jy)	S_P (Jy)	χ (degrees)	Q (Jy)	U (Jy)
			0048-097		
09-02-72	1.39±.02	--------	---------	----------	----------
01-14-73	2.14±.04	.013±.027	69.4±58.9	-.0100±.0360	.0088±.0064
04-06-73	1.84±.11	.031±.017	86.4±16.0	-.0305±.0177	.0039±.0057
05-27-73	1.54±.05	.041±.016	81.3±11.3	-.0394±.0171	.0123±.0048
08-20-73	1.59±.02	.016±.016	103.9±28.5	-.0145±.0183	-.0076±.0038
11-16-73	1.51±.04	.062±.015	91.5±06.9	-.0616±.0151	-.0032±.0042
02-27-74	1.68±.02	.064±.013	89.8±06.0	-.0637±.0134	.0005±.0055
06-28-74	1.89±.09	.040±.028	85.2±20.5	-.0391±.0290	.0066±.0083
11-25-74	1.95±.03	.072±.010	82.3±03.8	-.0696±.0102	.0191±.0032
03-02-75	1.81±.07	.044±.022	101.6±14.4	-.0405±.0240	-.0174±.0089
06-14-75	1.69±.05	.059±.021	76.9±09.9	-.0534±.0228	.0262±.0074
08-19-75	1.42±.03	.065±.010	89.1±04.6	-.0647±.0106	.0020±.0034
11-17-75	1.58±.05	--------	---------	----------	----------
02-22-76	1.73±.05	.072±.017	87.9±06.6	-.0718±.0171	.0052±.0062
08-28-76	1.49±.05	.068±.005	90.0±02.0	-.0684±.0058	.0000±.0022
12-03-76	1.36±.02	.056±.006	93.1±03.1	-.0553±.0062	-.0060±.0035
04-06-77	1.33±.02	.049±.009	83.6±05.0	-.0479±.0088	.0109±.0044
07-19-77	1.41±.02	.037±.005	94.9±03.8	-.0369±.0052	-.0063±.0025
11-17-77	1.51±.03	.041±.009	88.4±06.1	-.0411±.0089	.0023±.0027
05-01-78	1.02±.03	.033±.020	102.9±17.7	-.0299±.0226	-.0144±.0048
09-10-78	1.10±.04	.026±.008	95.9±09.2	-.0254±.0086	-.0053±.0028
12-09-78	1.32±.05	.037±.012	98.9±09.2	-.0356±.0127	-.0115±.0035
05-13-79	1.36±.03	.017±.006	86.4±09.3	-.0170±.0056	.0022±.0052
10-22-79	.91±.02	.015±.004	98.7±08.3	-.0147±.0047	-.0046±.0024
04-07-80	1.33±.05	.017±.011	178.4±19.7	.0166±.0115	-.0009±.0122
08-08-80	1.59±.03	.043±.013	83.9±08.9	-.0421±.0137	.0091±.0024
12-11-80	1.30±.04	.015±.009	65.9±17.3	-.0097±.0125	.0109±.0040
02-06-81	1.45±.03	.021±.011	96.4±15.5	-.0204±.0116	-.0046±.0032
			0607-157		
09-02-72	1.32±.07	--------	--------	----------	----------
01-13-73	1.71±.06	.017±.032	20.2±54.6	.0126±.0412	.0108±.0062
04-06-73	2.02±.11	.020±.011	57.7±15.6	-.0087±.0235	.0184±.0055
05-27-73	1.91±.11	.073±.037	5.3±14.6	.0716±.0387	.0134±.0099
08-20-73	2.12±.08	.073±.051	34.3±20.1	.0267±.0910	.0681±.0424
11-17-73	2.15±.08	.045±.036	83.2±23.0	-.0433±.0369	.0105±.0065
02-28-74	2.24±.07	.055±.021	79.7±10.7	-.0518±.0222	.0195±.0054
06-28-74	1.87±.07	.021±.048	15.0±63.9	.0185±.0548	.0107±.0063
11-25-74	1.66±.06	.061±.020	81.5±09.1	-.0588±.0207	.0179±.0062
03-02-75	1.65±.09	.035±.010	46.8±07.9	-.0022±.0290	.0347±.0099
06-14-75	1.76±.09	.066±.059	81.6±25.7	-.0632±.0619	.0190±.0130

TABLE I. (continued)

DATE	S_T (Jy)	S_P (Jy)	χ (degrees)	Q (Jy)	U (Jy)
08-19-75	1.45±.04	.027±.017	68.3±18.7	-.0193±.0232	.0183±.0058
11-18-75	1.38±.08	--------	---------	----------	----------
02-23-76	1.49±.03	.023±.005	33.0±06.3	.0094±.0080	.0210±.0042
08-28-76	1.73±.06	.014±.009	28.2±19.7	.0076±.0152	.0114±.0051
12-03-76	1.80±.07	.020±.009	56.2±12.8	-.0078±.0168	.0189±.0071
04-06-77	1.85±.07	.035±.013	57.6±10.5	-.0148±.0265	.0315±.0068
07-19-77	1.56±.06	.040±.012	23.9±08.4	.0268±.0166	.0295±.0053
11-18-77	1.61±.05	.014±.010	65.1±20.2	-.0087±.0135	.0103±.0050
04-30-78	1.60±.06	.014±.008	53.3±15.7	-.0040±.0174	.0136±.0063
09-09-78	2.00±.07	.024±.007	50.7±08.6	-.0046±.0178	.0232±.0065
12-11-78	1.99±.06	.030±.013	76.4±12.1	-.0271±.0140	.0139±.0072
05-13-79	1.66±.06	.013±.017	85.8±37.7	-.0125±.0168	.0018±.0066
10-23-79	1.43±.02	.015±.006	27.1±10.6	.0088±.0079	.0123±.0040
04-07-80	1.53±.11	.045±.013	80.4±08.2	-.0421±.0142	.0147±.0052
08-08-80	1.25±.04	.015±.012	66.5±22.8	-.0099±.0162	.0106±.0049
12-12-80	1.06±.04	.012±.013	83.3±30.7	-.0116±.0131	.0028±.0048
02-06-81	1.06±.04	.021±.019	75.7±25.2	-.0185±.0208	.0101±.0067
			0727-115		
09-02-72	2.40±.05	--------	---------	----------	----------
01-14-73	2.75±.04	.060±.028	173.2±13.1	.0587±.0284	-.0143±.0042
04-06-73	2.73±.04	.014±.012	170.9±25.7	.0133±.0131	-.0044±.0036
05-27-73	2.77±.08	.131±.038	2.1±08.2	.1306±.0391	.0097±.0089
08-19-73	3.03±.04	.141±.035	176.7±07.0	.1401±.0353	-.0161±.0055
11-17-73	2.71±.07	.013±.014	128.0±31.1	-.0031±.0323	-.0125±.0120
02-28-74	2.95±.04	.075±.012	91.8±04.4	-.0751±.0119	-.0047±.0033
06-29-74	3.50±.08	.031±.019	102.5±17.3	-.0285±.0208	-.0133±.0074
11-25-74	3.67±.04	.076±.015	98.2±05.6	-.0732±.0158	-.0217±.0089
03-02-75	3.55±.14	--------	---------	----------	----------
06-14-75	3.46±.09	.087±.036	86.8±11.6	-.0867±.0367	.0097±.0101
08-18-75	3.29±.05	.073±.017	84.8±06.5	-.0722±.0172	.0132±.0050
11-18-75	3.14±.04	--------	---------	----------	----------
02-23-76	2.83±.03	.002±.006	156.1±97.4	-.0013±.0088	-.0014±.0037
08-28-76	3.19±.07	.056±.017	91.8±08.6	-.0563±.0175	-.0035±.0118
12-04-76	2.67±.03	.037±.006	87.3±05.0	-.0367±.0066	.0035±.0037
04-05-77	3.64±.11	.042±.007	58.9±04.6	-.0195±.0124	.0368±.0056
07-19-77	3.48±.03	.049±.011	83.2±06.6	-.0471±.0116	.0115±.0042
11-18-77	3.16±.05	.030±.007	98.3±06.7	-.0286±.0075	-.0085±.0029
05-02-78	2.91±.04	.036±.012	94.2±09.5	-.0353±.0121	-.0052±.0035
09-10-78	2.93±.02	.042±.008	89.4±05.4	-.0420±.0080	.0009±.0041
12-11-78	2.75±.05	.035±.008	105.8±06.2	-.0296±.0087	-.0182±.0040
05-11-79	2.80±.11	.051±.009	107.5±05.2	-.0419±.0121	-.0294±.0050
10-22-78	2.67±.07	.028±.005	118.5±05.3	-.0151±.0082	-.0232±.0036

TABLE I. (continued)

DATE	S_T (Jy)	S_P (Jy)	χ (degrees)	Q (Jy)	U (Jy)
04-06-80	2.40±.04	.020±.007	109.4±10.4	-.0155±.0089	-.0125±.0032
08-08-80	2.15±.05	.018±.006	163.4±10.0	.0147±.0071	-.0097±.0031
12-12-80	2.12±.02	.007±.007	167.8±29.4	.0060±.0074	-.0028±.0023
02-06-81	2.16±.03	.034±.008	176.7±07.1	.0338±.0085	-.0039±.0030
			2200-420		
09-02-72	6.02±.10	--------	---------	----------	----------
01-14-73	4.41±.04	.106±.030	3.5±08.2	.1048±.0307	.0128±.0069
04-06-73	4.01±.04	.128±.019	179.9±04.3	.1278±.0199	-.0004±.0044
05-27-73	4.83±.07	.033±.031	169.3±26.5	.0308±.0327	-.0121±.0089
08-20-73	6.90±.10	.116±.028	97.2±06.9	-.1127±.0309	-.0290±.0116
11-16-73	7.13±.06	.102±.026	106.5±07.2	-.0858±.0304	-.0556±.0100
02-28-74	5.62±.06	.016±.021	27.8±38.9	.0088±.0252	.0129±.0191
06-29-74	6.03±.06	.197±.022	92.5±03.1	-.1962±.0246	-.0169±.0084
11-26-74	5.37±.11	.307±.025	100.1±02.2	-.2885±.0409	-.1058±.0192
03-02-75	2.68±.05	.071±.021	108.4±08.6	-.0572±.0259	-.0426±.0099
06-14-75	2.84±.05	.073±.025	97.9±10.0	-.0702±.0264	-.0199±.0108
08-18-75	2.97±.03	.080±.027	113.7±09.8	-.0538±.0398	-.0585±.0060
11-19-75	3.26±.05	--------	----------	----------	----------
02-22-76	3.38±.06	.095±.017	119.1±05.1	-.0501±.0279	-.0811±.0115
08-27-76	6.67±.08	.157±.033	113.9±05.9	-.1056±.0246	-.1167±.0398
12-03-76	5.43±.02	.306±.007	113.2±00.6	-.2109±.0089	-.2215±.0073
04-06-77	4.93±.11	.190±.018	117.4±02.6	-.1096±.0250	-.1553±.0227
07-19-77	5.09±.05	.205±.006	109.9±00.9	-.1574±.0098	-.1308±.0082
11-16-77	3.65±.02	.158±.004	117.4±00.8	-.0910±.0057	-.1288±.0040
05-01-78	3.22±.03	.116±.007	127.4±01.7	-.0304±.0158	-.1121±.0070
09-09-78	3.04±.07	.080±.004	125.3±01.4	-.0265±.0057	-.0751±.0064
12-10-78	2.40±.06	.089±.008	122.7±02.5	-.0368±.0146	-.0806±.0072
05-14-79	2.33±.03	.063±.010	116.2±04.4	-.0385±.0144	-.0499±.0055
10-22-79	2.27±.08	.064±.007	112.8±03.0	-.0446±.0098	-.0454±.0049
04-07-80	2.64±.04	.048±.014	101.5±08.2	-.0442±.0149	-.0187±.0056
08-08-80	7.55±.10	.225±.009	86.1±01.1	-.2230±.0234	.0302±.0110
12-11-80	6.35±.06	.081±.022	106.4±07.7	-.0681±.0226	-.0438±.0205
02-06-81	7.11±.06	.191±.010	130.4±01.5	-.0308±.0264	-.1884±.0153

II. OBSERVATIONS

The measurements were made at 2.7 GHz with the NRAO 300-ft (91 m) transit telescope. The details of the observing techniques and the reduction procedures are given by Kapitzky (1976). The source transits three beams, two of which are polarization switched, while one is load switched, to give the Stokes parameters *I*, *Q*, and *U*. Observing sessions were typically of one week duration and were scheduled approximately every four months. In order to increase the signal-to-noise ratio, observations taken during this week were combined to derive an average total flux density and polarization. Thus our data are not sensitive to events occurring on time scales of less than four months. Our data for the quasi-stellar objects 0048 − 097, 0607 − 157, 0727 − 115, and 2200 + 420 are presented in Table I. The individual sources are discussed below. Except where noted, identifications and redshifts are taken from the compilation of Hewitt and Burbidge (1980).

III. DISCUSSION

0048 − 097 is a BL Lacertae type quasar (Strittmatter *et al.* 1974) with a core-halo radio structure with about 0.1 Jy at 4.8 GHz located in the 7″ diameter halo and ~1.5 Jy concentrated in a core of size $\theta \sim 0\farcs4 \times 10^{-3}$ (Weiler and Johnston 1980). VLA observations at 20 cm by Perley (1982) and Wardle, Moore, and Angel (1983) reveal an extended secondary component with a flux density of $\sim 0.05 \pm 0.01$ Jy.

Our 2.7-GHz observations of the total flux density, polarization position angle, and polarized flux density are presented in Fig. 1(a). The source is a very active radio variable with at least six major outbursts in an 8-yr period [cf. Altschuler and Wardle 1976 (AW); Kesteven, Bridle, and Brandie 1976; Andrew *et al.* 1978]. Both increases and decreases in total flux density of roughly 50% occur with a time scale of a few months. The flux density outbursts appear to be superimposed on a slowly varying component which decreases gradually after 1975. The variations in polarized flux density occur with a ~5-yr time scale, and appear to be associated with the slowly varying component rather than the short time scale outbursts. The dominant feature in the polarized flux density is a very broad peak at ~0.07 Jy between mid-1975 and mid-1976, followed by a very gradual decline to about 0.02 Jy by mid-1979. The decline in polarized flux density is accompanied by a decline in fractional polarization.

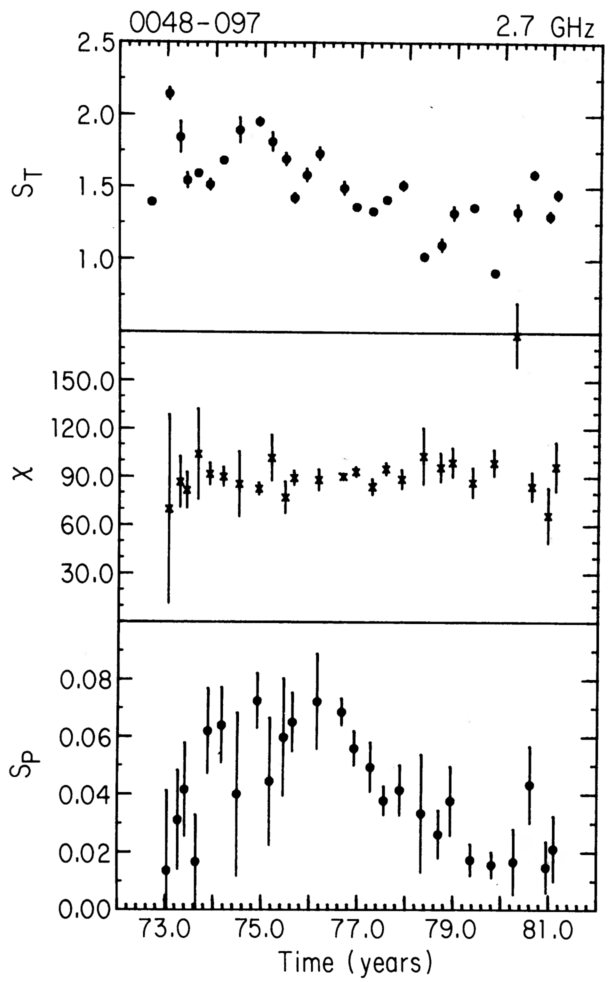

FIG. 1(a). 0048 − 097: 2.7-GHz total flux density S_T, polarization position angle χ, and polarized flux density S_p, as a function of time.

The apparent stability of the position angle at $90° \pm 1.5°$ during the 8-yr period is in sharp contrast with the variations in both the total and polarized flux density. Altschuler and Wardle (1976) also observe no large amplitude changes in position angle at 2.7 GHz during the period 1973 to mid-1975 when our data overlap. AW find a higher fractional polarization at 8 GHz than at 2.7 GHz; though the fractional variations at the two frequencies are comparable. We can conclude: (1) If the source polarization is dominated by a strongly polarized constant component (e.g., an extended component), we would expect both the position angle and polarized flux density to be fairly constant. The factor-of-4 change in the polarized flux density excludes this possibility. (2) The short time scale outbursts are unpolarized (depolarized?) at 2.7 GHz. The correlation of the slowly varying component with the polarized flux density suggests that this is the dominant variable polarized component at low frequencies. (3) The absence of a change in the position angle at 2.7 GHz suggests that there is no change in opacity from opaque to transparent or vice versa, and the polarized component is either always transparent or always opaque.

Altschuler (1980) reports a rotation of ~260° at 8 GHz between May 1974 and February 1975. The evolution of the total flux density spectrum between 2.7 and 31.4 GHz at four epochs during this period is presented in Fig. 1(b). The rotation reported by Altschuler begins prior to the 1974–75 outburst and ends shortly after the outburst peaked at 8 GHz. The pre-outburst spectrum of 1973.4 shows the broad spectral shape characteristic of either a single inhomogeneous component or a superposition of multiple narrower peaked components (e.g., Marscher 1977). The entire spectrum rose at all frequen-

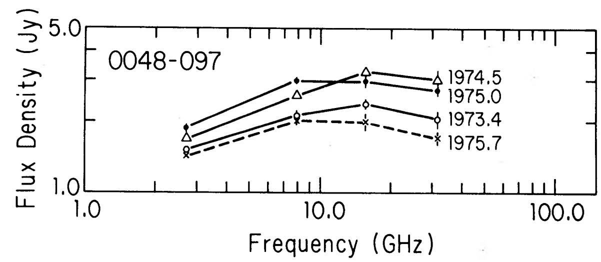

FIG. 1(b). 0048 − 097: Evolution of the radio spectrum at four epochs. The data points at 7.9 and 15.5 GHz were obtained with the Haystack Observatory 120-ft antenna, and those at 31.4 GHz (and at 89.6 GHz in the other figures) were obtained with the NRAO 36-ft telescope at Kitt Peak.

cies between 1973.4 and 1974.5, indicating that the outburst was broadband ($\geqslant$30 GHz) and probably inhomogeneous. The peak in the spectrum moved towards lower frequencies with time, peaking near 15 GHz in 1974.5 and 7.9 GHz at 1975.0. Then between 1975.0 and 1975.7 the entire spectrum fell while the peak remained near 8 GHz. The spectrum between 2.7 and 8 GHz was always inverted. The magnitude of the flux density change was less at 2.7 GHz than at the higher frequencies (e.g., $\delta S = 0.5$ Jy vs $\delta S = 1.0$ Jy at 7.8 GHz). All the evidence suggests that much of the flux density in this outburst originated in a region which was opaque at 2.7 GHz during the 8-GHz polarization rotation. Similar analysis of other outbursts during the 8-yr period strongly suggests that the source was mostly opaque at 2.7 GHz throughout the duration of our observations at this frequency.

We conclude that the outbursts and the position angle rotations observed in 0048 — 097 occur within a core which becomes opaque near 2.7 GHz. The depolarization of the outbursts at 2.7 GHz is probably due to synchrotron opacity. At 2.7 GHz the observed polarized flux density is due to a slowly decaying transparent component in the unresolved core.

0607–157 is a QSO with a redshift of $z = 0.324$. It is unresolved at $\sim 1''$ resolution at 4.8 GHz (Ulvestad *et al.* 1981). This source is much more variable in total flux density than in polarization. At 2.7 GHz the flux density has undergone three large outbursts with time scales of 1–2 yr [Fig. 2(a)] during the 8-yr duration of our observations. The changes in polarized flux density tend to follow those seen in total flux density, implying that the outbursts are polarized at a level of 2%–3%. The changes in position angle are only slightly correlated with the outbursts and vary over a range of about 60°. These position angle variations are at least a factor of 2 smaller at 2.7 GHz than those at higher frequencies reported by AAH. They observe a position angle rotation at 8 GHz between 1977.5 and 1978.1 whose amplitude is uncertain but may be as much as 180°. At 2.7 GHz, the fractional polarization averages $\sim 1.5\%$, with typical variations of $\sim 0.7\%$; while at 8 GHz the fractional polarization averages $\sim 3\%$ with typical variations of $\sim 2\%$ (AAH).

The downturn in the radio spectrum [Fig. 2(b)] suggests that the core of the source was substantially opaque at 2.7 GHz during the time of the 8-GHz rotation in 1977. The spectrum at 1977.3 is comprised of two components, a decaying, flat centimeter-wavelength component which may be the remnant of previous outbursts, and a new rising outburst at millimeter wavelengths that is very broadband (~ 100 GHz). The new outburst reached a maximum near 1977.9 as the peak frequency of the outburst drifted to lower frequencies. By 1979.8 the spectrum of the outburst has decayed such that the total flux density spectrum peaks below 2.7 GHz.

0727 — 115 is unresolved at $\sim 1''$ resolution at 4.8 GHz (Ulvestad *et al.* 1981). The source is very interest-

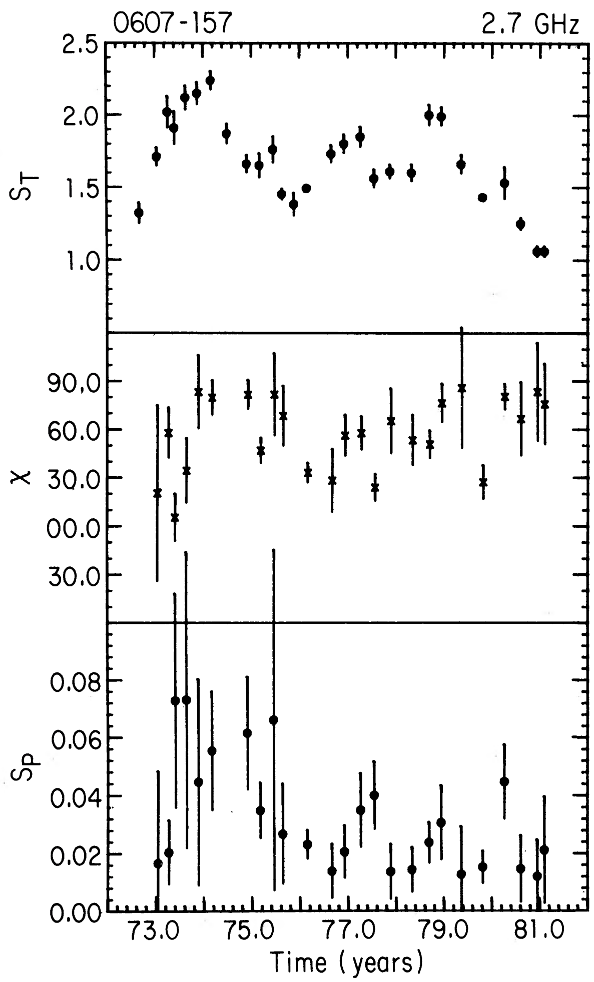

FIG. 2(a). 0607 — 157: Same as Fig. 1(a).

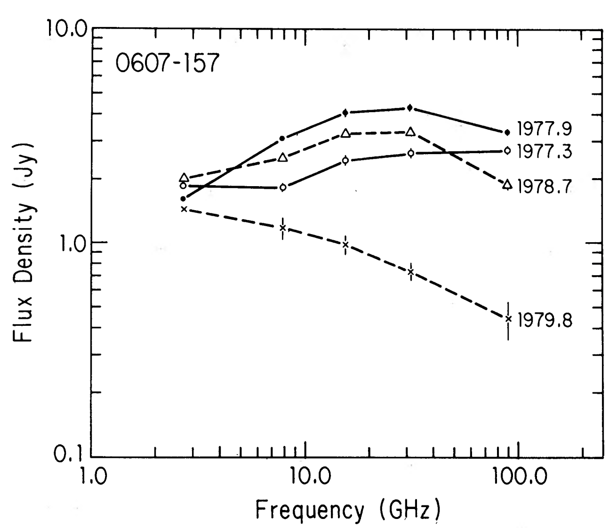

FIG. 2(b). 0607 — 157: Evolution of the radio spectrum at four epochs.

ing because AHA have observed a position angle rotation of roughly 106°/yr between mid-1977 and late 1980. The changes in position angle seem to occur mainly in four discrete jumps each less than 90°, with in general only minor variations between the jumps. There appear to be quasi-sinusoidal variations in polarized flux density with a period of roughly six months (AHA; L. Molnar, 1982 personal communication). Inspection of the variability data between 1973 and 1982 [from our data (2.7–90 GHz); AHA (4.8, 8.0, and 14.5 GHz); and Andrew *et al.* 1978 (10.6 GHz)] reveals the following scenario for 0727 − 115. After a year of minor variations, a 2-Jy amplitude outburst peaked around 1975.0 at frequencies from 10.6 to 2.7 GHz. By 1976 this outburst had decayed to a flux density level just above the pre-outburst level. In mid-1976 another outburst began at frequencies between 2.7 and 31.4 GHz peaking simultaneously at all frequencies in early 1977. While this outburst was decaying, a third event occurred which peaked in early 1978 at 31.4 and 15.5 GHz, while at 7.9 and 2.7 GHz an event peaked in mid-1979. Whether or not the latter event is the early 1978 outburst delayed or an independent event is unclear. Following these events, the flux density dropped steadily at frequencies between 90 and 2.7 GHz with the total flux density leveling out beginning in late 1980 at all frequencies in this range.

In summary, the general trend in flux density until late 1980 has been a steady decrease since the 1977 outburst, with one or two major outbursts (1978/79) and minor fluctuations superimposed upon this trend. The decay since 1977 is shown by the spectra in Fig. 3(b). The individual outbursts previously mentioned are not obvious due to the coarse time resolution in this figure. Because of the many overlapping outbursts the evolution of the spectrum [Fig. 3(b)] is complex. In 1976.2 the spectral maximum was near 8 GHz. Between 1976.2 and 1977.3 the spectrum below 8 GHz rose (as the opacity decreased?). The spectrum above 8 GHz also rose as a new outburst appeared at all wavelengths shifting the peak in the spectrum up to ∼15 GHz. After the spectrum peaked in 1977.3 the entire spectrum below 90 GHz fell and the spectral peak moved back to ∼8 GHz. A more rapid decay above 15 GHz produced a sharp break in the spectrum by 1980.2 while the 2.7-GHz flux density remained roughly constant.

Three of the four jumps in position angle (between 55 and 82 deg) observed by AHA during the general decay correspond in time to the peaks of the above outbursts. The 8-GHz data of AHA indicate that the percentage polarization dropped to near zero at each of these four events (though this is not as clear in 1980).

Our 2.7-GHz data [Fig. 3(a)] show a position angle change of about 90° in late 1973 as the series of outbursts began. Between 1974 and 1980 the position angle varied only slightly with a total range of ∼20° about 90°. However, in mid-1980 the position angle returned to its 1973 value within a period of four months. This return coincides with the cessation of outburst activity. It therefore appears that the outbursts all have a similar magnetic field orientation which is at a large angle to the field in a constant background component. The fractional polarization at 2.7 GHz is ∼1.2%, with typical variations of

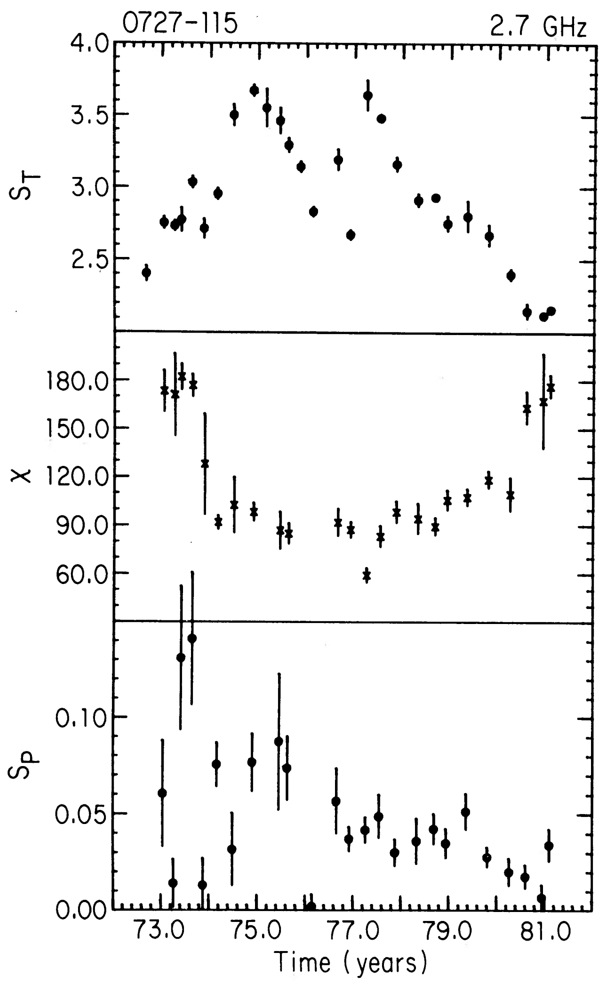

FIG. 3(a). 0727 − 115: Same as Fig. 1(a).

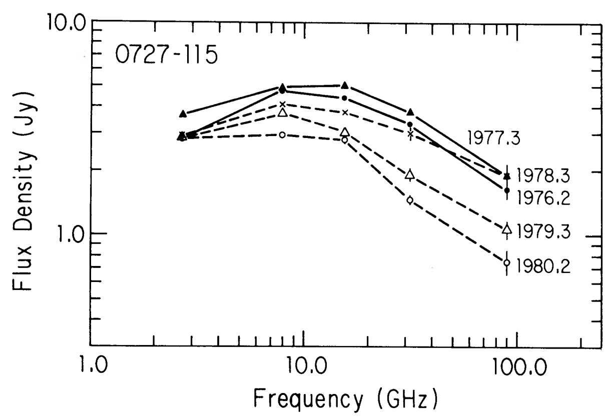

FIG. 3(b). 0727 − 115: Evolution of the radio spectrum at five epochs.

$\sim 0.4\%$; while at 8 GHz, these values are 2% and 2%, respectively (AAH).

The large amplitude position angle changes observed between 4.8 and 14.5 GHz (AHA) support an interpretation in terms of a rotating structure either on an accretion disk (Pineault 1980) or in a jet (Hodge, Aller, and Aller, 1982 personal communication), though there are problems with both models (L. Molnar, 1982 personal communication). Another possibility is that each of the position angle changes is produced by a separate outburst originating in a region of differing magnetic field orientation. This hypothesis would, however, require that the magnetic field is arranged in such a way as to produce a systematic trend in the position angle. The association of the position angle jumps with the outbursts noted above suggests a third possibility in which a continuously rotating magnetic field occurs behind a screen with variable opacity. Each time the screen becomes transparent the position angle is seen in its new orientation. When the screen is opaque no rotation is seen. In this model the lack of observed polarization rotation at 2.7 GHz results from the opacity never dropping below unity. However, this simple model would not reproduce the apparent step-like behavior in position angle or the quasi-sinusoidal variations in polarized flux density. At present there does not appear to be a satisfactory explanation for the polarization variations in 0727 − 115.

2200 + 420 (BL Lac) ($z = 0.07$) has no extended structure larger than $\sim 1''$ at 4.8 GHz (Ulvestad, Johnston, and Weiler 1983). VLBI measurements (Pearson and Readhead 1981) show a core ($\theta \sim 0\overset{''}{.}0005$) and a two-component jet (oriented North-South) whose length is $0\overset{''}{.}010$. Phillips and Mutel (1982) find that this structure changes on a time scale of a few months and suggest that BL Lac exhibits superluminal motion.

Our 2.7-GHz measurements of the total flux density, polarized flux density, and polarization angle are presented in Fig. 4(a). The source is very variable in all three quantities and some changes are not adequately sampled by our observations (see Reich and Steffen 1982; Johnston *et al.* 1983). Even at as "low" a frequency as 2.7 GHz the outbursts are strongly polarized with occasional maxima greater than 5%. In general, the average fractional polarization at 2.7 GHz is $\sim 3\%$ with typical variations of $\sim 1\%$. At 8 GHz, the fractional polarization averages $\sim 3.5\%$, and exhibits typical variations of $\sim 2\%$ (AAH).

A flux density outburst began in early 1973 and peaked (with $\delta S = 3.5$ Jy) in 1974.0. During this time the position angle rotated by 90° from 0°/180° to 90° with superimposed more rapid fluctuations (AW). The polarized flux density also flickered rapidly at this time.

The 1973 outburst was immediately followed by an outburst in early 1974 and another which began in early 1975. The latter peaked in late 1976, and slowly decayed with two shoulders which could be additional outbursts of smaller amplitude. Both the fractional polarization

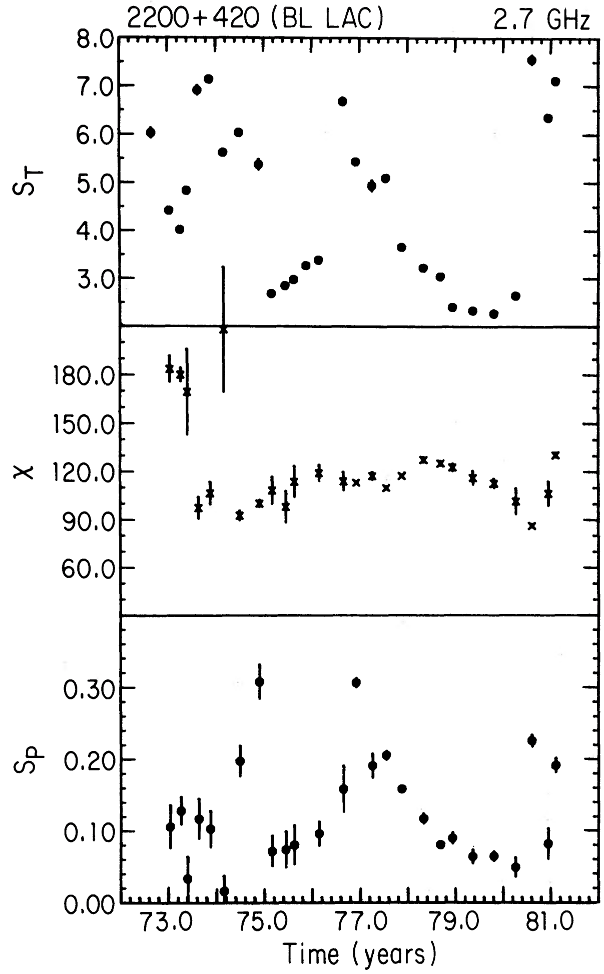

FIG. 4(a). 2200 + 420: Same as Fig. 1(a).

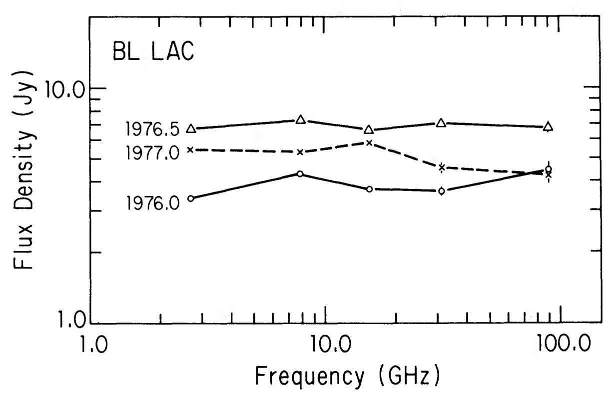

FIG. 4(b). 2200 + 420: Evolution of the radio spectrum at three epochs.

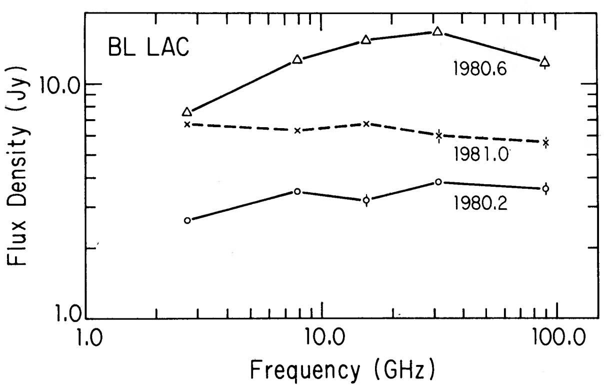

FIG. 4(c). 2200 + 420: Evolution of the radio spectrum at three epochs.

and the polarized flux density followed the changes in total flux density. During this time the position angle exhibited only minor changes. The position angle was relatively constant until after the peak of the outburst in 1976 when it began a slight drift.

The evolution of this outburst is shown in Fig. 4(b). The spectra are generally flat, though they contain bumps which may be due to nonsimultaneous observations when the flux density is changing rapidly. The entire spectrum between 2.7 and 89.6 GHz rose between 1976.0 and 1976.5 and fell between 1976.5 and 1977.0. Because of the high percentage polarization and a factor-of-6 change in the polarized flux density, the absence of a large position angle rotation cannot be attributed to confusion by another polarized component. The flat spectrum suggests that the outburst was inhomogeneous. The absence of a 90° change in position angle at all frequencies shows that the outburst was always mostly transparent.

The outburst which began in late 1979 and peaked in mid-1980 was accompanied by variations in polarized flux density of about a factor of 2. AHA observed a roughly 12°/day nonlinear rotation in position angle with a total range of about 440° in this outburst. The rotation was seen at 4.8 GHz and above, though the rotation at 4.8 GHz was delayed slightly with respect to the higher frequencies (H. Aller, 1982 personal communication). At 2.7 GHz we observed a $\sim 15°$ change during the same time period. The rapid rotation would not have been seen in the 2.7-GHz data because of the long sampling interval. However, the difference in the pre- and post-outburst position angles at the higher frequencies is about 80° ($+2\pi$) and is roughly five times that observed at 2.7 GHz.

The dip near 15.5 GHz in the 1980.2 spectrum before the outburst [Fig. 4(c)] suggests that at that time the source consisted of at least two spectral components. The entire spectrum (both spectral components?) rose between 1980.2 and 1980.6. There was a broad peak in the spectrum near 30 GHz in 1980.6. The spectrum flattened as the outburst decayed between 1980.6 and 1981.0. Although the outburst was probably inhomogeneous and mostly transparent, the curvature in the spectrum suggests that the core was opaque at 2.7 GHz during the time of the rotation. This would explain why the 440° rotation seen above 4.8 GHz was not observed at 2.7 GHz.

IV. CONCLUSIONS

The polarization position angle variations at 2.7 GHz are smaller in amplitude than those observed at higher frequencies. The $\geqslant 180°$ changes in position angle observed at 8 GHz in 0048 − 097, 0607 − 157, 0727 − 115, and 2200 + 420 are not seen at 2.7 GHz. The fractional polarization at 8 GHz tends to be higher than that at 2.7 GHz. With the exception of 0048 − 097, the fractional variations in percentage polarization are also higher at 8 GHz. However, some of this difference could be due partly to the longer sampling interval at 2.7 GHz. The large changes in polarized flux density at 2.7 GHz (as well as the general lack of strong extended structure on both the arcsecond and milliarcsecond scales) suggest that there is only a very small contribution to the polarization from nonvarying components, and that this emission originates in the core. The evolution of the radio spectra reveals that the flux density variations are extremely broadband (~ 100 GHz) and suggest that the outbursts originate in inhomogeneous regions [e.g., with a "tapered" structure; Condon and Dressel (1973), Marsher (1977)]. The low-frequency curvature in the radio spectra of these four sources suggests that the core of the emitting region is substantially opaque at 2.7 GHz during the time of the rotations. 0048 − 097 may always be opaque at this frequency. The "low frequency cutoff" in the large polarization rotations observed at higher frequencies is probably due to synchrotron opacity in a region surrounding the rotating core.

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