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COORDINATED CENTIMETER, MILLIMETER, INFRARED, AND VISUAL POLARIMETRY OF COMPACT NONTHERMAL SOURCES

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ABSTRACT

Nearly simultaneous polarization data have been obtained at centimeter, millimeter, infrared, and visual wavelengths for 0851+20 (OJ 287) and 2200+42 (BL Lac) and (excepting infrared) for 0735+17. In addition, centimeter and millimeter data have been obtained for 0235+16, 1226+02 (3C 273), and 1641+39 (3C 345). The degree of polarization generally tends to increase toward shorter wavelengths. For OJ 287, the 3 mm polarization ($m = 12.4\%$) approaches the value found at 2.28 μm ($m = 17\%$). The data in several cases imply little or no Faraday rotation. In OJ 287 the polarization angle is similar from 3.7 cm to 0.44 μm, and in BL Lac the degree and position angle of the polarization are similar at 0.44 μm, 2.28 μm, and 3 mm. These results indicate the existence of a common emission mechanism and region, producing radiation from visual to at least millimeter wavelengths.

Subject headings: BL Lacertae objects — polarization — quasars

I. INTRODUCTION

The polarization of QSOs and BL Lacertae objects has been studied for a number of years at both visual and radio wavelengths (e.g., Strittmatter *et al.* 1972; Visvanathan 1973; Altschuler and Wardle 1975; Ledden and Aller 1978). Unfortunately, there have been few coordinated observations involving both regions. This has made it difficult to relate the properties of one spectral region to another, especially for variable sources. At centimeter wavelengths, sources are typically 3%–10% linearly polarized and variable on time scales of months to years (e.g., Altschuler and Wardle 1976). By contrast, visual polarizations of 10%–30% are not uncommon and may well vary on time scales of days or weeks (e.g., Visvanathan 1973; Stein, O'Dell, and Strittmatter 1976). By combining nearly simultaneous data obtained at several wavelengths in both parts of the spectrum, one can begin to distinguish the effects of structure, opacity, and birefringence. One may also hope to gain significant insight into the physical relationships which exist between radio and visual emitting regions. Previous searches for correlated variability (e.g., Kinman *et al.* 1974; Pomphrey *et al.* 1976) and continuity of spectrum (O'Dell *et al.* 1978) have indicated this type of physical relationship for some sources.

This *Letter* describes the first observations in a program of coordinated polarization observations at centimeter, millimeter, infrared, and visual wavelengths. Earlier millimeter wave polarimetry has involved measurements at only a single wavelength (Hobbs 1968; Wardle 1971; Hobbs, Maran, and Brown 1978). The infrared and millimeter wave polarization properties of compact sources are still largely unknown. We therefore chose, in this initial, exploratory effort, to observe sources thought to have the greatest detectability in these two bands. Future observations will examine more uniformly selected source samples.

II. OBSERVATIONS

Data at 11.1 cm and 3.7 cm were obtained on 1977 November 22–23, using the NRAO three-element interferometer. Polarization parameters were derived for about 15 sources, using standard methods (Altschuler and Wardle 1976). Sources which were bright and/or particularly highly polarized at that epoch were then observed on 1977 December 2–5 at 9 mm and on 1977 December 5–7 at 3 mm with the NRAO 10.6 m telescope on Kitt Peak. Observations at 2.28 μm were obtained on 1977 December 7–8 and at 0.44 μm on 1977 December 11–12 with the UM-UCSD 1.5 m telescope on Mount Lemmon. Additional 0.44 μm polarimetry data were obtained on 1978 January 7–8 and February 3–4.

Observing procedures at Kitt Peak and Mount Lemmon will be detailed elsewhere, but we note here the following important features. At 9 mm the receiver was a dual-channel mixer, with a system temperature of ~650 K and a bandwidth of 1 GHz. The two orthogonal linear feed polarizations were stationary on the (altazimuth) telescope. It was therefore necessary to utilize variation of the parallactic angle[1] with hour

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[1] The angle between the hour circle and the vertical circle passing through a point on the sky.

angle to separate the Q and U Stokes parameters. Each source was observed as long as practical to obtain good coverage in parallactic angle. At 3 mm, a single-channel cooled mixer, with a system temperature of ~325 K and a bandwidth of 1 GHz, was used. Two quarter-wave plates (one rotatable) were used to generate the required linear polarizations at 45° increments. Observations of Jupiter, Saturn, and DR 21 (all assumed unpolarized) were made to determine the instrumental polarization. Our results have been corrected accordingly.

The 0.44 μm and 2.28 μm observations were obtained with a single-channel polarimeter, using a chopping secondary for sky compensation. The polarization analyzer allowed linear polarization observations at 45° increments. At 2.28 μm, an H-R type (Polaroid Corporation) analyzer was used with a solid-nitrogen-cooled InSb detector. At 0.44 μm an HNPB (Polaroid Corporation) analyzer was used with an RCA C31034 photomultiplier pulse-counting system. The relatively insignificant instrumental polarization was determined by observing nearby unpolarized standard stars, and corrected for in our results.

The normalized Stokes parameters and their errors were derived by a least-squares analysis of the data on each source. The conversion to mJy was made by observing sources of known flux density. For some of the visual and infrared data, additional direct photometric observations, made immediately before or after the polarimetric measurements, were used. The resulting uncertainties from these procedures have been included in the quoted errors for I, Q, and U.

The fractional polarization $[m = I^{-1}(Q^2 + U^2)^{1/2}]$ and position angle $[\chi = \frac{1}{2}\tan^{-1}(U/Q)]$ were calculated in the normal way, correcting m for the bias due to noise (Wardle and Kronberg 1974). The errors in m and χ were determined from the appropriate extrema of the skew error ellipse in the (Q, U)-plane. This procedure is equivalent to the standard method of quoting errors $[\Delta m \approx (2/N)^{1/2}(\sigma/I);\ \Delta\chi \approx \frac{1}{2}(\Delta m/m)]$ when $\Delta Q \sim \Delta U \ll (Q^2 + U^2)^{1/2}$. It is more appropriate when this limiting case is not obtained. When the signal-to-noise ratio $\lesssim 2$, the interpretation of the standard errors is not straightforward. The probability distribution for the true values of m is not Gaussian. Also, because values of χ are restricted to be in the [0°, 180°] range, there is ~5% probability that χ is completely undefined when $m/\Delta m \approx 2$. Hence we have not quoted errors on m and χ for low signal-to-noise measurements, and one should instead utilize the quoted rms errors in Q and U, which are Gaussian. The quoted uncertainties in position angle at 9 mm and 3 mm include a 3° error, added in quadrature, to allow for uncertainties in our absolute determination of angles on the sky.

III. RESULTS

The results of these observations are tabulated in Table 1. Column (1) gives the PKS-type source designation and other source names. The date of observation is in column (2), and the observing wavelength in column (3). Columns (4), (5), and (6) contain the measured Stokes parameters I, Q, and U along with their rms errors. The fractional polarization and position angle are given with their errors in columns (7) and (8).

The data obtained on several sources deserve special comment.

i) *0735+17*.—The general properties of this and the other known BL Lacertae objects have been reviewed by Stein, O'Dell, and Strittmatter (1976; see also Altschuler and Wardle 1975 for radio properties). This source exemplifies the typical increase in fractional polarization between radio and visual wavelengths. Radio and visual position angles differ by ~60°, but the close similarity of the two centimeter wave angles (even as they vary with time; Altschuler and Wardle 1976) is evidence against this difference being due to Faraday rotation. Our data, along with those of Rieke *et al.* (1977), confirm the results of Carswell *et al.* (1974) that the visual polarization is highly variable in both degree and position angle. Rieke *et al.* observed a difference between the infrared and visual polarization angles. This may be due to time variability. If not, it will be important to follow the change in angle through the millimeter regime to the value at centimeter wavelengths.

ii) *0851+20* (OJ 287).—Except for the 11.1 cm value, the position angles in the radio regime are essentially the same, viz., 85°–90°. The data of Altschuler and Wardle (1976) indicate that this angle has remained relatively constant at 3.7 cm since early 1974, and that in 1974–1975 the position angle at 11.1 cm was also near 90°. This angle is different from the ~75° observed at 2.28 μm and 0.44 μm, but is variable on a short time scale. Since 1972, the average visual position angle has also been ~90° (Shakhovskoy and Efimov 1977). Particularly at the short radio wavelengths the flux density of OJ 287 was notably stronger in our observations than it was in early 1977 (O'Dell *et al.* 1978). The spectrum at the epoch of these observations seems to peak between 9 mm and 3 mm. This most likely indicates a transition from optically thin to partially optically thick toward wavelengths longward of a few millimeters. The significant increase in degree of polarization from 9 mm to 3 mm is consistent with this interpretation (e.g., Jones and O'Dell 1977*a*, *b*). See Figure 1.

All these characteristics point to a strong relationship among the visual, infrared, and radio emitting regions. It suggests that the visual-infrared source lies within the radio source; i.e., they are not independent "components." This conclusion is strengthened by the fact that OJ 287 is one source in which visual and radio variability seem to be strongly correlated (Kinman *et al.* 1976; Pomphrey *et al.* 1976).

It is noteworthy that the polarization position angle is so constant for two other reasons. First, it strongly limits any Faraday rotation within the source. As has been pointed out (Jones and O'Dell 1977*a*, *c;* Wardle 1977), this indicates that relativistic electrons within the source greatly outnumber nonrelativistic electrons. Second, the position angle does not change significantly as the source becomes partially opaque, whereas in

TABLE 1

Source (1)	Date (2)	Wavelength Band (3)	I(mJy) (4)	Q(mJy) (5)	U(mJy) (6)	m(%) (7)	χ(°) (8)
0235+16.....	77 Nov 22–23	11.1 cm	1910±50	−53±5	0±5	2.8±0.3	90±6
	77 Nov 22–23	3.7 cm	2030±140	−27±6	+28±6	1.9±0.3	67±6
	77 Dec 2–5	9 mm	2800±140	−97±45	−35±30	∼3.7	∼100
0735+17.....	77 Nov 22–23	11.1 cm	1830±60	−34±5	+5±5	1.9±0.3	84±6
	77 Nov 22–23	3.7 cm	1820±170	−35±6	+1±6	1.9±0.4	89±6
	77 Dec 7–5	9 mm	1670±80	+74±50	+10±30	∼3	...
	77 Dec 11	0.44 μm	2160±90	+180±30	−20±10	12.5±0.9	157±2
	78 Jan 7–8	0.44 μm	1940±40	+140±20	−130±4	9.8±0.9	158±2
	78 Feb 3–4	0.44 μm	1300±40	+20±30	−17±20	13±2	139±4
0851+20 (OJ 287)...	77 Nov 22–23	11.1 cm	1940±30	+15±5	−52±5	2.8±0.3	143±4
	77 Nov 22–23	3.7 cm	3500±125	−254±11	+74±5	7.5±0.3	82±3
	77 Dec 2–5	9 mm	5150±260	−430±77	−45±54	8.2±1.5	93±6
	77 Dec 5–7	3 mm	4850±240	−605±77	−31±77	12.4±1.5	92±6
	77 Dec 7	2.28 μm	20.8±0.9	−2.9±1.1	+2.1±1.4	17±5	72±10
	77 Dec 11	0.44 μm	2.9±0.2	−0.63±0.06	+0.37±0.02	25±1	75±1
	78 Jan 6–7	0.44 μm	3.1±0.1	−0.87±0.04	+0.17±0.02	28.4±0.8	84.4±1
	78 Feb 3–4	0.44 μm	2.4±0.1	−0.33±0.04	+0.24±0.01	17±1	72±2
1226+02 (3C 273)...	77 Nov 22–23	11.1 cm*	44300	+620	−880	2.4±0.3	153±4
	77 Nov 22–23	3.7 cm*	28800	+230	−200	1.0±0.3	159±10
	77 Dec 2–5	9 mm	29400±1500	+650±30	−830±30	3.6±0.1	154±3
	77 Dec 5–7	3 mm	14940±750	+570±100	−660±100	5.8±0.7	153±4
1641+39 (3C 345)...	77 Nov 22–23	11.1 cm	7320±110	−8±8	+227±8	3.1±0.3	46±3
	77 Nov 22–23	3.7 cm	7140±240	+173±9	+145±10	3.2±0.3	20±4
	77 Dec 2–5	9 mm	7180±360	−109±93	+159±75	∼2.5	∼60
2200+42 (BL Lac)...	77 Nov 22–23	11.1 cm	3400±40	−84±10	−173±10	5.6±0.3	122±4
	77 Nov 22–23	3.7 cm	3190±160	−121±5	+154±14	6.1±0.4	64±4
	77 Dec 2–5	9 mm	2610±130	−120±57	+82±70	∼5	∼75
	77 Dec 5–7	3 mm	2160±110	+128±69	−15±70	∼5	∼0
	77 Dec 7	2.28 μm	59.4±6.1	+3.0±0.7	−2.9±1.7	7±2	158±8
	77 Dec 11	0.44 μm	2.5±0.1	+0.19±0.02	0±0.02	7.6±0.8	0±3

* The interferometer coverage on 3C 273 did not allow an accurate measure of the integrated flux density for the three Stokes parameters. The values quoted are based on Högbom's "clean" deconvolution, with estimated errors of ∼10%.

some cases one expects a 90° rotation (e.g., Aller 1970; Jones and O'Dell 1977*a*). However, as Jones and O'Dell (1977*b*) have demonstrated, this expectation may be peculiar to sources with sharp boundaries. In a "tapered" source, capable of producing the kind of gradual spectral turnover observed here (Condon and Dressel 1973; de Bruyn 1976; Marscher 1977), most of the polarized flux would be produced just outside of the optically thick core, and would have a characteristic position angle appropriate to the optically thin emission.

iii) *1226+02* (3C 273).—Combining our data with other measurements of the integrated polarization, we see that the position angle remains near 150° at all radio wavelengths (see Inoue 1977 for references). The degree of polarization is a complicated function of wavelength; it has a broad local maximum of ∼3% at ∼10 cm, and rises again to ∼6% at 3 mm. The visual and infrared polarization are weak and variable (see Kemp *et al.* 1977 and references therein). After the major variations in mid-1966 (Aller 1970), no large changes in the radio polarization have been reported (see Bignell and Seaquist 1972; Seielstad and Berge 1975; Efanov *et al.* 1977).

Our 3 mm fractional polarization and position angle differ from the values obtained recently by Hobbs *et al.* and disagree with the predictions of Inoue (1977). The data again seem to imply an almost total absence of Faraday rotation. VLBI data for this source show it to be elongated at position angle ∼60° (e.g., Cohen *et al.* 1977), nearly at right angles to the plane of polarization, suggesting a magnetic field orientation parallel to the major axis of the central source. The more extended "jet" is at position angle 223° (Hazard, Gulkis, and Bray 1966).

iv) *2200+42* (BL Lac).—The degree of polarization observed in BL Lac seems to be roughly the same in both spectral regions. Our data give visual and infrared position angles ∼0°, close to the range of values found by Knacke, Capps, and Johns (1976). The position angle at 3 mm is less certain, but is nominally also ∼0°. At longer wavelengths, however, the angle is distinctly different. This change is not simply explained by Faraday rotation or, since the spectrum seems to peak below 11.1 cm, by opacity effects.

The visual polarization angle of BL Lac is variable, but no long-term average is apparent (Shakhovskoy and Efimov 1977). The 3.7 cm and 11.1 cm polarization angles each vary by about 100° over the time scales of of years (Altschuler and Wardle 1976). However, their

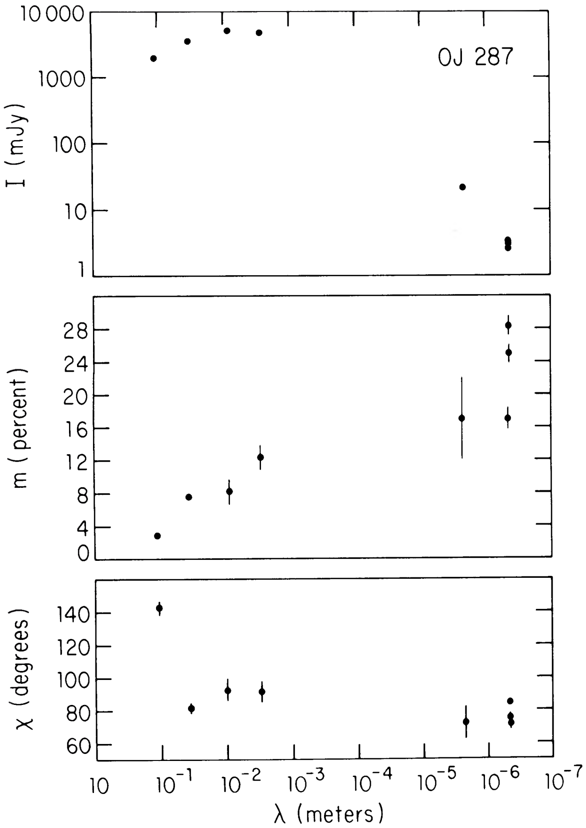

FIG. 1.—The total intensity and polarization observed for OJ 287 as a function of wavelength, from the data in Table 1.

difference is characteristically ~60°, as in these observations.

VLBI observations show extended structure along position angle ~0, at centimeter wavelengths (Kellermann *et al.* 1977). To connect these various observations of BL Lac may require a more complicated picture than discussed for OJ 287, but additional coordinated data are certainly necessary.

IV. CONCLUSIONS

In these initial observations we have examined the polarization characteristics of two QSOs at radio wavelengths (3C 273, 3C 345), three BL Lacertae objects (0735+17, OJ 287, and BL Lac) in both radio and visual-infrared regimes, and the BL Lacertae object 0235+16 at radio wavelengths.

In general these data show an increase in the degree of polarization toward short radio wavelengths, in agreement with the findings at 2 cm by Ledden and Aller (1978). It is premature to identify a single, general cause for this effect. At least in the case of OJ 287, however, the decrease in polarization expected toward long wavelength with increasing opacity is probably an important factor. Our data are as yet insufficient to enable us to make general statements concerning the amount of Faraday rotation in compact sources (but see, e.g., Wardle 1977); however, in 3C 273, OJ 287, and BL Lac, the simplest interpretation of the data would involve little or no Faraday rotation.

Perhaps the most interesting result here is OJ 287's relatively high degree of polarization and nearly constant position angle at all but the longest radio wavelength. These indicate a common radiation process (presumed here to be synchrotron) and common emitting region over this wide range of wavelengths. At least to 3 mm there is weaker evidence for this in BL Lac, as well. Thus we have evidence for a single entity responsible for nonthermal radiation extending into the ultraviolet from the radio band. Such objects may provide a prototype for the radiation source in QSOs and active galactic nuclei, which are required for photoionization and production of emission lines (see, e.g., Williams *et al.* 1975; Weedman 1977).

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REFERENCES

Aller, H. D. 1970, *Ap. J.*, **161**, 19.
Altschuler, D. R., and Wardle, J. F. C. 1975, *Nature*, **255**, 306.
———. 1976, *Mem.* R.A.S., **82**, 1.
Bignell, R. C., and Seaquist, E. R. 1972, *A.J.*, **78**, 536.
Carswell, R. F., Strittmatter, P. A., Williams, R. E., Kinman, T. D., and Serkowski, K. 1974, *Ap. J.* (*Letters*), **190**, L101.
Cohen, M. H., *et al.* 1977, *Nature*, **268**, 405.
Condon, J. J., and Dressel, L. L. 1973, *Ap. Letters*, **15**, 203.
de Bruyn, A. G. 1976, *Astr. Ap.*, **52**, 439.
Efanov, V. A., Moiseev, I. G., Nesterov, N. S., and Shakhovskoy, N. M. 1977, *Nature*, **269**, 493.
Hazard, C., Gulkis, S., and Bray, A. D. 1966, *Nature*, **210**, 888.
Hobbs, R. W. 1968, *Ap. J.*, **153**, 1001.
Hobbs, R. W., Maran, S. P., and Brown, L. W. 1978, *Ap. J.*, **223**, 373.
Inoue, M. 1977, *Pub. Astr. Soc. Japan*, **29**, 593.
Jones, T. W., and O'Dell, S. L. 1977*a*, *Ap. J.*, **214**, 522.
———. 1977*b*, *Ap. J.*, **215**, 236.
Jones, T. W., and O'Dell, S. L. 1977*c*, *Astr. Ap.*, **61**, 291.
Kellermann, K. I., *et al.* 1977, *Ap. J.*, **211**, 658.
Kemp, J. C., Rieke, G. H., Lebofsky, M. J., and Coyne, G. V. 1977, *Ap. J.* (*Letters*), **215**, L107.
Kinman, T. D., Wardle, J. F. C., Conklin, E. K., Andrew, B. H., Harvey, G. A., MacLeod, J. M., and Medd, W. J. 1974, *A.J.*, **77**, 349.
Knacke, R. F., Capps, R. W., and Johns, M. 1977, *Ap. J.* (*Letters*), **210**, L69.
Ledden, J. E., and Aller, H. D. 1978, private communication.
Marscher, A. P. 1977, *Ap. J.*, **216**, 244.
O'Dell, S. L., Puschell, J. J., Stein, W. A., Owen, F., Porcas, R. W., Mufson, S. M., Moffett, T. J., and Ulrich, M. H. 1978, *Ap. J.*, **224**, 22.
Pomphrey, R. B., Smith, A. G., Leacock, R. J., Olsson, C., Scott, R. L., Pollock, J. T., Edwards, P., and Dent, W. A. 1976, *A.J.*, **81**, 489.

Rieke, G. H., Lebofsky, M. J., Kemp, J. C., Coyne, G. V., and Tapia, S. 1977, *Ap. J.* (*Letters*), **218**, L37.
Seielstad, G. A., and Berge, G. L. 1975, *A.J.*, **80**, 271.
Shakhovskoy, N. M., Efimov, Yu. S. 1977, *Izv. Crimean Ap. Obs.*, **56**, 39.
Stein, W. A., O'Dell, S. L., and Strittmatter, P. A. 1976, *Ann. Rev. Astr. Ap.*, **14**, 173.
Strittmatter, P. A., Serkowski, K., Carswell, R., Stein, W. A., Merrill, K. M., and Burbidge, E. M. 1972, *Ap. J.* (*Letters*), **175**, L7.
Visvanathan, N. 1973, *Ap. J.*, **179**, 1.
Wardle, J. F. C. 1971, *Ap. Letters*, **8**, 183.
———. 1977, *Nature*, **269**, 563.
Wardle, J. F. C., and Kronberg, P. P. 1974, *Ap. J.*, **194**, 249.
Weedman, D. W. 1977, *Ann. Rev. Astr. Ap.*, **15**, 69.
Williams, R. E., Strittmatter, P. A., Carswell, R. F., and Craine, E. R. 1975, *Ap. J.*, **202**, 296.

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