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SIMULTANEOUS VISUAL-INFRARED POLARIMETRY OF QSOs

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ABSTRACT

Simultaneous visual and infrared polarimetry shows transient evidence for wavelength dependent polarization in some QSOs. At other times and in other sources, polarization is wavelength independent. The wavelength coverage of our measurements (2.2–0.36 μm) allows us to begin to test various possible causes of wavelength dependent polarization. Contamination by unpolarized starlight or scattering off asymmetric clouds of electrons, atoms, or grains probably can be excluded as a major contributing effect in 0754+101 (OI 090.4). Faraday rotation inside that source can explain the data only if one invokes multiple spectral domains. Likewise, one can account for the observations by invoking spectral components with differing polarization properties; for example, by including spectral breaks due to electron energy losses. Detailed observations of the evolution of wavelength dependent polarization are needed to test these models. Understanding this phenomenon will provide important information about conditions in the core regions which produce visual-infrared continuum in QSOs.

Subject headings: infrared: sources — polarization — quasars

I. INTRODUCTION

A potentially powerful method for probing the compact emission regions of QSOs is to study the polarization as a function of wavelength. The degree of visual wavelength polarization of compact extragalactic objects ranges from roughly 40% for some BL Lac objects to only a percent or so for nearly all the classical QSOs studied (see the review by Angel and Stockman 1980). The plausible causes of this polarization include scattering off asymmetric distributions of free or bound electrons or dust and nonthermal emission such as synchrotron radiation arising in an anisotropic magnetic field. Large amplitude polarization variations observed on time scales as short as a day have led to a general acceptance of the synchrotron explanation for nearly all sources with degrees of polarization larger than about 1%.

It has been known for some time that the degree and plane of polarization of synchrotron radiation from a power-law distribution of electrons are wavelength independent (e.g., Ginzburg and Syrovatskii 1965). The optical spectra of many optically violently variable QSOs (OVVs) do resemble power laws (e.g., O'Dell, Puschell, and Stein 1977; Neugebauer *et al.* 1979), and most measurements of the spectral dependence of the polarization in the optical and infrared of OVVs are consistent with the above expectations of the simplest synchrotron model (e.g., Visvanathan 1973; Knacke, Capps, and Johns 1976, 1979; Rieke *et al.* 1977; Puschell and Stein 1980). However, a few results have indicated significant wavelength dependence to the polarization (e.g., Nordsieck 1976; Rieke *et al.* 1977; Moore *et al.* 1980; Puschell and Stein 1980; Impey *et al.* 1982). Both the degree of polarization and position angle have been observed to depend on wavelength in several sources on at least one occasion.

The usefulness of many previous observations in interpreting this phenomenon has been reduced by limited wavelength coverage (e.g., $U-R$ bands), very limited coverage within the observed range of wavelengths [e.g., B (0.44 μm) and K (2.2 μm) bands] or nonsimultaneous observations at the different bands. Since detailed and broad wavelength coverage is necessary to distinguish among various possible explanations, we have initiated a program of simultaneous visual-infrared multiband

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TABLE 1

OBSERVATIONS

Date	$\lambda(\mu m)$	F_ν(mJy)	%P	θ_{max}
		0735+178		
1979 Nov 24	0.43	1.70±0.10	27.9±2.1	21.1±2.2
	0.55	2.50±0.15	24.5±2.9	26.3±3.4
	0.69	3.47±0.17	23.5±1.7	19.7±2.1
1979 Nov 27	0.36	1.25±0.14	25.6±4.0	22.3±4.4
	0.43	1.78±0.18	29.8±2.1	20.1±2.1
	0.55	2.7±0.3	28.0±3.0	23.3±3.1
	0.69	3.6±0.4	25.2±1.3	23.3±1.5
1980 Apr 7	0.43	...	31.6±2.1	22.3±1.9
	2.2	...	23.5±2.5	...
1980 Apr 8	0.69	...	33.2±2.1	24.2±1.8
	2.2	...	25±5	...
1980 Apr 9	0.43	...	32.2±1.6	22.9±1.2
	0.69	...	36.9±1.6	23.7±1.2
	1.6	...	32.0±3.5	22.8±3.1
	2.2	...	32.6±2.7	17.4±2.4
		0754+101		
1979 Nov 24	0.36	2.45±0.15	17.7±2.3	46.2±3.7
	0.43	3.46±0.21	20.0±1.2	52.5±1.8
	0.55	4.81±0.29	16.6±1.8	54.0±3.0
	0.69	6.73±0.34	17.8±1.5	49.7±2.4
1979 Nov 27	0.43	3.9 ±0.4	15.7±1.8	44.4±3.3
	0.55	5.2 ±0.6	16.4±2.2	40.4±3.9
	0.69	7.1 ±0.8	15.3±1.0	35.8±1.8
1980 Apr 5	0.43	...	27.8±1.9	35.7±2.0
1980 Apr 6	0.43	...	25.5±2.0	35.5±2.3
	0.69	...	20.6±1.8	37.5±2.5
	2.2	...	11.4±1.7	...
1980 Apr 9	0.43	...	23.1±1.9	39.8±2.3
	0.69	...	18.8±1.5	39.2±2.3
	1.6	...	12.4±2.3	34±5
	2.2	...	13.2±2.1	31±5
1981 Feb 20	0.36	...	20±5	75±7
	0.43	...	15.7±1.9	66±4
	0.55	...	14.7±2.7	60±5
	0.69	...	13.6±1.3	57.8±2.7
	2.2	...	10.8±1.1	53±5
		0754+101 (*cont.*)		
1980 Mar 5	0.43	...	12.7±2.2	108±5
1980 Mar 6	2.2	...	14.6±2.2	...
1980 Mar 7	0.69	...	9±3	103±12
	2.2	...	13.4±2.0	...
1980 Mar 8	0.69	...	5.1±2.5	115±15
	2.2	...	0±4	...
1980 Mar 9	0.43	...	12.9±1.6	111±4
	1.6	...	11.6±3.1	103±8
	2.2	...	12.1±2.5	103±6
		1308+326		
1980 Mar 8	0.3–0.9	...	18±4	121±6
1980 Mar 9	0.3–0.9	...	20±3	140±4
		1418+546		
1980 Mar 9	0.43	...	13±3	137±7
	2.2	...	0±2	...
		2200+420		
1979 Nov 23	0.43	1.92±0.12	14.2±3.3	6.1±6.7
	0.55	4.23±0.21	18.9±2.6	14.7±3.9
	0.69	9.0±0.5	18.2±2.0	15.1±3.2
1979 Nov 25	0.36	1.00±0.06	16.6±2.9	24.5±5.0
	0.43	2.88±0.76	7.5±1.8	22.9±6.8
	0.55	6.4±0.7	10.8±1.3	20.6±3.5
	0.69	12.3±1.0	9.6±0.9	20.4±2.5
1979 Nov 27	0.36	1.02±0.13	18.1±6.9	11.8±11.5
	0.43	2.14±0.21	7.5±2.6	29.3±10.0
	0.55	5.1±0.6	9.2±2.1	28.8±6.6
	0.69	9.9±1.2	14.8±0.6	15.1±1.1
1979 Nov 28	2.28	80±3	9.8±1.8	20.3±5.3

(U, B, V, R, K) polarimetry of several OVVs and BL Lac objects with previously observed wavelength dependent polarization. We emphasize that these observations are truly simultaneous at the different bands. We report here initial polarimetry results in this program along with associated photometry. Section II describes the observations and summarizes the results. Section III discusses in detail the results for 0754+101. Comparable observations of 0235+164 have been recently reported by Impey *et al.* (1982) and are briefly discussed below.

II. OBSERVATIONS AND RESULTS

Data were obtained using the UCSD/UM Mount Lemmon 1.5 m telescope during 1979 November, 1980 April, and 1981 February and the KPNO 2.1 m telescope during 1980 April and 1981 February. A telephone link between the two observatories was maintained during the 1980 April and 1981 February sessions so that observations could be coordinated.

The procedures for obtaining and reducing the Mount Lemmon data have been described by Puschell *et al.* (1979) and Puschell and Stein (1980). The Kitt Peak measurements were carried out with BT (Blue Toad) photometer and two polarimeters—one containing a rapidly rotating polarizer and the other using a polarizer driven in increments of 45° by a stepping motor. In both cases, the polarizer was an aluminum wire grid with a BaF_2 substrate.

The polarimetry and photometry are summarized in Table 1. The degree of polarization is corrected for noise bias (Wardle and Kronberg 1974).

The 1979 November observations were coordinated with polarimetry at centimeter wavelengths using the

VLA and millimeter wavelengths using the NRAO 11 m telescope on Kitt Peak. Those data were obtained within a week of the optical data and are discussed elsewhere (Rudnick *et al.* 1982). The coordinated observations were part of a program aimed at studying the relationship between the optical and radio polarization in active sources (Rudnick *et al.* 1978; Puschell *et al.* 1979). These earlier papers described observations of similar radio and optical degrees and angles of polarization in 0851+203 (OJ 287) and possibly 1308+326. More extensive observation such as those in 1979 November have not established such simple relationships in other objects. However, due to significant day-to-day variability in the optical polarization, it may be difficult to identify "characteristic" optical position angles (e.g., Kinman 1977) without long-term monitoring. To a lesser degree this same problem exists at radio wavelengths on a longer time scale (Rudnick *et al.* 1982).

Our principal concern here is wavelength dependent polarization in the visual-infrared region. The clearest examples in these data are for 0754+101 (OI 090.4) in 1980 April (when a strong wavelength dependence was seen in the degree of polarization) and 1981 February (when a $\sim 25°$ rotation in position angle was observed between 2.2 μm and 0.36 μm). The next section focuses on that source. Other possible indications of wavelength dependence are in the data of 0735+178 (1980 April 7) and 1418+546 (1980 April 9). These data all suggest a reduced degree of polarization at longer wavelengths. All the other multiband data are consistent with an absence of wavelength dependence to the polarization.

III. DISCUSSION

The existence of occasional wavelength dependent visual-infrared polarization in 0754+101 now seems hard to deny. Rieke *et al.* (1977) reported a position angle rotation on one occasion of almost 30° between 0.52 μm ($58° \pm 3°$) and 2.2 μm ($26° \pm 3°$). Puschell and Stein (1980) also saw marginal evidence for a smaller rotation (10°) of the same sign between 0.36 μm and 2.2 μm during 1978. Our data from 1981 February 20 show a clear and systematic position angle rotation between 0.36 μm and 2.28 μm (see Fig. 2). Data from 1980 April display an obvious and significant ($\sim 7\ \sigma$) decrease in the degree of polarization from 0.43 μm to 2.2 μm. On the other hand, no such effects are evident at other times (e.g., Table 1, 1979 November 24).

Since we measure the polarization at as many as five wavelengths, we can begin to test various potential causes of wavelength dependence. Wavelength dependence can be introduced by Faraday rotation or other complications in a synchrotron source, or it could indicate a completely different origin for some or all of the polarized emission. Examples of explanations of the latter kind include scattering from an asymmetric screen or absorption by a dichroic medium (aligned dust grains, for example). We will now examine these effects.

a) *Contamination by Nonsynchrotron Light*

We can immediately exclude contamination of a synchrotron source by unpolarized starlight as the sole cause of wavelength dependence in 0754+101, since that cannot rotate the plane of polarization. On the other hand, it is easy to show that the wavelength dependence observed in both 1980 April and 1981 February could be understood as a combination of a wavelength independent polarization component plus an added polarization vector whose length decreased at longer wavelengths but whose position angle was wavelength independent.[3] Rayleigh scattering by small solid particles or by electrons bound in atoms or molecules could produce an effect if the scatterers were distributed asymmetrically around the central source. In fact if one assumed that the polarization at 2.2 μm was uncontaminated, the added polarization vector on both dates would be roughly consistent with a λ^{-4} (Rayleigh scattering law) degree dependence, reaching $\sim 10\%-20\%$ in the *U* band. The position angle of the scattered component would be $\sim 45°$ in 1980 April and $\sim 90°$ in 1981 February.

The magnitude of the polarization required to be produced in this way ($\gtrsim 10\%$) necessitates that the scattering screen subtend a large solid angle as seen by the source [$\gtrsim 4\pi/(10 \sin^2 \phi)$, where ϕ is the scattering angle]. Substantial changes in this component over an interval of months or less then would require that the screen be closer than a few light months from the central source, and much closer if the day-to-day changes in wavelength dependence seen in 0235+164 (Impey *et al.* 1982) also apply to 0754+101. Solid particles would quickly vaporize at any such distances. A distance limit cannot be set for aligned, absorbing grains, but a very large extinction and reddening would be necessary.

To consider scattering by bound electrons, one should note that an observed wavelength dependent polarization produced in this way requires that scattering by free electrons (Thomson scattering) not dominate Rayleigh scattering, since Thomson scattering is wavelength independent. The ratio of Rayleigh to Thomson scattered fluxes will be approximately (e.g., Jackson 1975)

$$\frac{S_R}{S_T} \sim \frac{N_R}{N_e}\left[\sum_n f_n \left(\frac{\lambda_n}{\lambda}\right)^2\right]^2,$$

where f_n and λ_n are the oscillator strength and transition wavelength of each contributing transition. N_R and N_e are the atomic and free electronic densities. One must require that $S_R/S_T \gtrsim 1$, and since $\lambda_n/\lambda \ll 1$ by defini-

[3] This is easily seen through Argand diagrams, for example.

tion and $f_n \lesssim 1$, it would be necessary that $N_R/N_e \gg 1$, i.e., the scattering medium must be largely neutral. Mostly neutral clouds may exist near QSOs if they are capable of absorbing all the Lyman photons incident on them. However, the covering factor required to produce the observed polarization in 0754+101 is > 10%, at least as great as that thought to be typical in strong line quasars (e.g., Davidson and Netzer 1979), whereas 0754+101 is a BL Lac object with no emission lines. Since the spectral index in 0754+101 is close to that for typical quasars ($\alpha \sim 1.1$) so that an ionizing continuum probably exists, the absence of strong emission lines probably excludes Rayleigh scattering as a significant source of polarization. In sources with a weak Lyman continuum, this limitation would not apply, of course.

b) *Faraday Effects*

The most straightforward means to modify the simple synchrotron model polarization is Faraday rotation, since that can produce both a rotation of the polarization plane with wavelength and wavelength dependent depolarization, if the Faraday rotation is occurring in the source itself. This was suggested for 0754+101 by Rieke *et al.* (1977). (The simplest sort of Faraday rotation picture involving an intervening screen cannot explain the strong wavelength dependence seen in the degree of polarization and therefore will not be considered here.)

For a homogeneous spherical source, the angle of rotation for small Faraday depths is given by (e.g., Burn 1966)

$$\Delta\Theta\,(\text{degrees}) \approx 5.6\times 10^{-24}\langle n_e B_{\parallel}\rangle l\lambda^2_{\mu\text{m}},$$

where $\langle n_e B_{\parallel}\rangle$ is the characteristic product of the electron density and parallel magnetic field component through the source, l is the diameter, and $\lambda_{\mu\text{m}}$ is the wavelength in microns. The formula relating $\langle n_e B_{\parallel}\rangle$ and $\Delta\Theta$ becomes more complex as $\Delta\Theta$ approaches 45° (e.g., Burn 1966; Cioffi and Jones 1980). $\Delta\Theta$ tends to be a constant for large Faraday depths, except in the case of a plane-parallel source. Depolarization occurs whenever the Faraday depth is not identical for all parts of the source in the field of view.

Figure 1 shows an example of a simple Faraday model fit to the 0754+101 data for 1980 April 9. The solid lines represent rotation in a homogeneous spherical source with $\langle n_e B_{\parallel}\rangle l = -1\times 10^{24}(1+z)^2$ gauss cm^{-2}. In a formal χ^2 sense, this best fitting Faraday model is not a very good description of the data because the $\chi^2/r = 4.6$ (with r, the degrees of freedom equal to 5) and the probability of observing a value this large in a random sample is much less than 1%. The best fitting homogeneous spherical Faraday model to the data of 1981 February 20 (see Fig. 2) [$\langle n_e B_{\parallel}\rangle l = -6\times 10^{23}(1+z)^2$ gauss cm^{-2}] is characterized by a $\chi^2/r = 2.1$ and a random sample probability with 7 degrees of freedom of about 5%. The fact that both data sets for 0754+101 are fit poorly by Faraday rotation in a homogeneous spherical source argues strongly against this interpretation of wavelength dependent visual-infrared polarization in 0754+101. (The choice of a spherical shape is not crucial to this argument—see Cioffi and Jones 1980.) This conclusion is reinforced by examining the 0235+164 data of Impey *et al.* (1982). For their data taken on 1979 December 12, the best fitting homogeneous spherical Faraday model (using $z = 0.852$ and $\langle n_e B_{\parallel}\rangle l = -1.1\times 10^{24}$ gauss cm^{-2}) gives $\chi^2/r = 4.8$ with a corresponding probability of much less than 1% (7 degrees of freedom). We are forced to conclude that the homogeneous Faraday model is not an adequate description of wavelength dependent polarization in these BL Lac objects.

A wide range of wavelength dependences is possible, however, in inhomogeneous sources subject to Faraday effects (see; e.g., Cioffi and Jones 1980). More complex models can be made to explain the data. For example, one might imagine the source to consist of two nonoverlapping regions (such as oppositely directed jets), one of which is subjected to stronger Faraday depolarization than the other. One can fit the 1981 February 20 data with such a model in which each of two regions are ~ 10% polarized, but one has an intrinsic position angle ~ 90° and $\langle n_e B_{\parallel}\rangle l \approx -10^{25}$ gauss cm^{-2}, while the other has an intrinsic position angle ~ 50° with a $\langle n_e B_{\parallel}\rangle l$ ten or more times smaller. Detailed analyses of such models are unjustified with current data, however.

The values of $n_e B_{\parallel}$ indicated in the above analyses ($\sim 10^8$–10^{10} gauss cm^{-3} if $l \sim 10^{15}$ cm) are not unreasonable in and around optical synchrotron components of QSOs (cf. Blandford and Rees 1978). The magnetic fields which yield maximum electron lifetimes ($\sim 10^3$ gauss, eq. [1]) would result in Faraday effects like those indicated, provided $n_e \sim 10^5$–10^6 cm^{-3}. These densities are comparable to those required in relativistic electrons ($n \sim 10^4$ cm^{-3} under similar assumptions). Since electron radiative lifetimes are probably very short (see discussion below and Blandford and Rees 1978), it is possible that most of the electrons are nonrelativistic.

c) *Spectral Domains*

Alternatively, polarization wavelength dependence would follow naturally if the physical location dominating emission varied with wavelength; i.e., there are spectral domains. This idea has also been employed by Moore *et al.* (1982) to explain the polarization behavior in 2200+42 (BL Lac). The number of different domains in the visual-infrared has to be small to produce the high degree of polarization observed in that part of the spectrum. Furthermore, the close correspondence between flux variations at different wavelengths in the

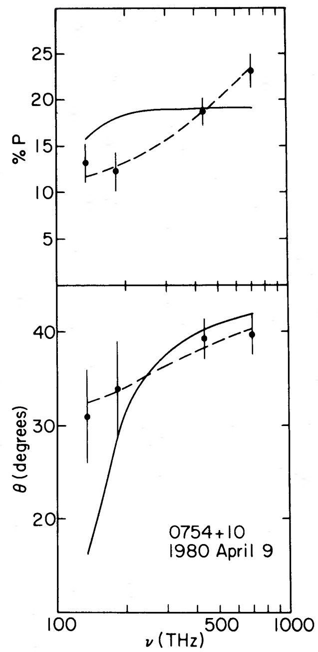

FIG. 1

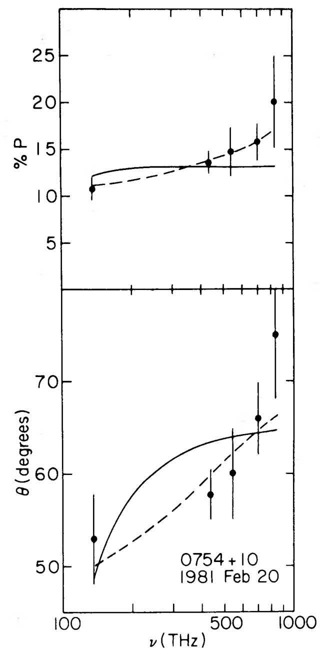

FIG. 2

FIG. 1.—Percentage of polarization and position angle for 0754+101 on 1980 April 9. The solid line represents the best fit for Faraday rotation in a homogeneous spherical source, and the dashed line represents the best fitting two component model with monoenergetic electron injection using $\nu_1 = 300$ THz and $\nu_2 = 1000$ THz.

FIG. 2.—Same as Fig. 1 except that data is for 1981 February 20

visual-infrared implies a close relationship between the domains (e.g., Rieke *et al.* 1976; O'Dell *et al.* 1978; Puschell *et al.* 1979).

Spectral domains capable of explaining the observed wavelength dependent polarization require a high-frequency spectral break. One plausible mechanism for producing a break in a visual-infrared synchrotron spectrum is radiative energy losses. It has been pointed out before that the radiative lifetimes of the electrons are very short in luminous visual-infrared sources at a given instant unless strong relativistic beaming is important (see, for example, Blandford and Rees 1978). In fact, the lifetimes are generally much less than light travel times across the source. Thus, because of retarded time effects, one sees emission at a given instant not only from electrons at their injected energies, but also at lower energies weighted according to their cooling rates (cf. Falla and Evans 1975).

To understand this note that the maximum electron lifetime corresponds approximately to the condition in which synchrotron and Compton energy losses are the same (e.g., Jones and Stein 1975). The resulting magnetic field is

$$B \approx \left(\frac{32\pi^2 S d^2}{\lambda l^2}\right)^{1/2} \sim 500\left(\frac{S_{\mathrm{mJy}} d_{\mathrm{Gpc}}^2}{\lambda_{\mu\mathrm{m}} l_{15}^2}\right)^{1/2} \text{ gauss,} \quad (1)$$

where S is the spectral flux and d is the distance. The lifetime to synchrotron and Compton losses is

$$t \sim 2\frac{\lambda_{\mu\mathrm{m}}^{5/4} l_{15}^{3/2}}{S_{\mathrm{mJy}}^{3/4} d_{\mathrm{Gpc}}^{3/2}} \text{ s.} \quad (2)$$

For 0754+101, $S_{\mathrm{mJy}} \sim 10$–30 at $\lambda_{\mu\mathrm{m}} \sim 2$, so that the radiative lifetimes are very short unless the distance d is quite small (the problem was also discussed by Hoyle, Burbidge, and Sargent 1966 and Blandford and Rees 1978). To compute the appropriate emission spectrum for electrons injected at energy $\gamma_0 mc^2$, one needs the steady state kinetic energy distribution $n_\gamma \sim n_0 \gamma^{-2}$ for $\gamma < \gamma_0$ (Kardashev 1962; Falla and Evans 1975), where γ is the electron Lorentz factor. The resulting volume emissivity is then approximately

$$\varepsilon_\nu \sim n_0 (\nu_B/\nu)^{1/2} \exp(-\nu/\nu_0) \quad (3)$$

with $\nu_0 \sim \gamma_0^2 \nu_B$ and synchrotron frequency ν_B. This spectrum has a break near ν_0.

Based on this result, the simplest spectral component source model might consist of a superposition of spectra of the form given by equation (3). Different source regions with different magnetic field strengths (and therefore different ν_0's) could in general have different field directions and/or degrees of ordering, leading quite naturally to wavelength dependent polarization.

In order to test this model as it applies to the available data, we have made least squares fits using spectra comprised of two domains of the form

$$S_i = K_i \nu^{-1/2} \exp(-\nu/\nu_i), \tag{4}$$

where $i = 1, 2$. Since the domains are not power laws, we must specify the wavelength dependence of the polarization for each component. We find in agreement with Nordsieck (1976) that a reasonable approximation is given by

$$m \propto (\alpha+1)/(\alpha+5/3), \tag{5}$$

where $\alpha \equiv -d \ln \varepsilon_\nu / d \ln \nu$ is the local slope of the emissivity curve. Thus, for each domain,

$$m_i = m_{i0}(\nu/\nu_i + 3/2)/(\nu/\nu_i + 13/6). \tag{6}$$

For a given set of data, only the normalization frequencies ν_1, ν_2 must be assumed.

Acceptable least squares fits to the 0754+101 data are possible for a wide range in ν_1 and ν_2. For instance, our polarization data for 1980 April can be described best in the usual χ^2 sense with fits using 100 THz $< \nu_1 <$ 600 THz and $\nu_2 >$ 800 THz. We can restrict the ν_2 range considerably by enforcing such obvious physical constraints as the requirement that each component be $<100\%$ polarized and by acknowledging the observed variability property of BL Lac objects that require much of the optical emission to arise in a single domain. The result is roughly 800 THz $< \nu_2 <$ 1800 THz. Table 2 shows the results for fits using $\nu_1 = 300$ THz and $\nu_2 =$ 1000 THz. (These values of ν_1 and ν_2 were chosen because both sets of data are well fitted with them.) Spectral-flux data from Puschell and Stein (1980) were used to constrain fits to the Stokes parameter I_ν (i.e., to determine K_1 and K_2). In the visual and near-infrared, I_ν is dominated by the 1000 THz component, although substantial variations in the 300 THz component would be noticed in the near-infrared if the two regions were physically unconnected. The dashed lines in Figures 1 and 2 represent these models.

This type of model also can fit the 0235+164 data of Impey *et al.* very well, although there is some difficulty fitting the spectral-flux distribution. However, the visual-infrared spectral fluxes for 0235+164 are very uncertain, because of the probability of large amounts of extinction associated with the coincident nebulosity (e.g., Burbidge *et al.* 1976; Roberts *et al.* 1976).

TABLE 2

Two-Domain Model Parameters

Date	m_{10} (%)	Θ_1	m_{20} (%)	Θ_2	χ^2/r	r
1980 Apr 9	38	147°	37	43°	0.70	2
1981 Feb 20 ...	39	10°	25	71°	0.43	4

Models based on monoenergetic electron injection produce rather sharp spectral breaks in each component. Furthermore, they may be unrealistic representations of electron injection mechanisms. Therefore, we have also considered equivalent models with an assumed power-law electron injection spectrum above a characteristic energy γ_0 which depends upon local conditions as before. Such models can represent the data about as well as those described in detail above. More sophisticated models, based on specific physical structures, for example, are unjustified without more detailed evidence of the spectral distribution and time development of wavelength dependent polarization. Clearly, it would be of great value to obtain simultaneous photometry and polarimetry at several different wavelengths in a manner permitting study of the time development of the polarization.

Because of the frequently observed rapid variability in the polarization, one should probably avoid attaching long-term labels to spectral domains. It seems more likely in the sort of picture explored here that electrons are injected at various times into regions with different field structures or that the field structures themselves evolve on time scales of a few days or less. If the emitting material is beamed toward us with magnetic fields aligned, then aberration can exaggerate the effect (e.g., Blandford and Königl 1979) causing apparently large changes in projected field orientation (i.e., plane of polarization) whenever small changes in the source geometry have occurred. Regardless of the details of how the changes occur, careful observations should reveal changes in the spectrum as the polarization evolves if the above picture is applicable. In sources like 0754+101, high-precision spectra should show significant deviations away from power laws. As mentioned earlier, it is already established that in general there is a good correlation between visual and infrared flux changes in some BL Lac objects (cf. Rieke *et al.* 1976; O'Dell *et al.* 1978). Therefore, it must be that a real physical connection exists between any spectral domains.

IV. CONCLUSIONS

1. Simultaneous polarimetry in the infrared and visual bands of some QSOs clearly shows evidence for wavelength dependent polarization on some occasions. On other occasions the wavelength dependence is small or absent.

2. One can reasonably exclude such extrinsic causes for the wavelength dependence as contamination by starlight, scattering by free electrons, or Rayleigh scattering off of atoms, molecules, or dust particles.

3. The wavelength coverage is sufficient to exclude Faraday rotation within a homogeneous source as the principal cause of wavelength dependence. However, more complex, inhomogeneous models involving Faraday rotation may explain the data. The physical conditions required to produce the necessary rotations are not unreasonable within the context of standard synchrotron models.

4. Other classes of inhomogeneous source models may also explain the data. For example, multiple spectral domain models based on spectral breaks due to radiative energy losses by the electrons can account for the data. Such spectral breaks seem very plausible given the extremely short radiative lifetimes for electrons in these sources.

5. The best means to discriminate between the different classes of models will be to observe in detail the time *and* wavelength flux and polarization behavior of events in which wavelength-dependent polarization occurs. Since the explanations carry important information about conditions in the radiating regions, it is clearly important to establish more fully the nature of the phenomenon.

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