

THE OUTBURST OF THE BLAZAR AO 0235+164 IN 2006 DECEMBER: SHOCK-IN-JET INTERPRETATION

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ABSTRACT

We present the results of polarimetric (*R*-band) and multicolor photometric (*BVRIJHK*) observations of the blazar AO 0235+16 during an outburst in 2006 December. The data reveal a short timescale of variability (several hours), which increases from optical to near-IR wavelengths; even shorter variations are detected in polarization. The flux density correlates with the degree of polarization, and at the maximum degree of polarization the electric vector tends to align with the parsec-scale jet direction. We find that a variable component with a steady power-law spectral energy distribution and very high optical polarization (30%–50%) is responsible for the variability. We interpret these properties of the blazar within a model of a transverse shock propagating down the jet. In this case a small change in the viewing angle of the jet, by $\lesssim 1^\circ$, and a decrease in the shocked plasma compression by a factor of ~ 1.5 are sufficient to account for the variability.

Subject headings: BL Lacertae objects: individual (AO 0235+164) — galaxies: active — galaxies: jets — polarization

Online material: machine-readable tables

1. INTRODUCTION

Blazars are active galactic nuclei (AGNs) that possess extreme properties, such as violent variability, high polarization, relativistic jets, and bright γ -ray emission. It is commonly thought that the radio-through-optical emission in blazars is synchrotron radiation that originates in the jets. Polarimetric observations provide crucial data for investigating the magnetic field structure that forms the framework of such radiation. However, the polarization behavior is usually too complex for straightforward interpretation. For example, long-term observations of BL Lacertae reveal a change of degree of polarization from 0.5% to >20% with all possible electric vector position angles (EVPAs), although the distribution of EVPAs indicates the existence of a preferential direction aligned with the parsec-scale jet (Hagen-Thorn et al. 1994). Difficulties are even more severe for physical models designed to explain both the brightness and polarization behavior. A connection between polarization and brightness is rarely seen at optical wavelengths (Smith 1996). However, there are strong indications that the optical polarized emission is linked to the millimeter-wave VLBI core of blazars jets (Lister & Smith 2000; Gabuzda et al. 2006; D’Arcangelo et al. 2007; Jorstad et al. 2007).

At radio wavelengths some progress in interpretation of both polarization and brightness variability has been achieved by using a model in which a shock propagates down the jet (e.g., Hughes et al. 1989). At optical wavelengths, where polarization and brightness can vary on timescale of a few hours (e.g., Hagen-Thorn 1972; Miller & Noble 1996; Carini 2006), a proper test of models requires very intensive monitoring of both polarization and brightness. Such simultaneous photometric and polarimetric

measurements are difficult to obtain, but they provide a vital tool for distinguishing among different models responsible for the variability.

We have observed the BL Lac object AO 0235+164 ($z = 0.94$) during the relatively short outburst in 2006 December as part of the polarimetric and photometric monitoring program of blazars that has been carried out at St. Petersburg State University for many years. AO 0235+164 shows extreme blazar properties, such as intraday variability (e.g., Raiteri et al. 2005) and very high apparent speeds in the radio jet, $\beta_{\text{app}} = (26 \pm 7)c$ (Piner et al. 2006), which have drawn the attention of many investigators to this object (Raiteri et al. 2001, 2005, 2006; Junkkarinen et al. 2004; Hagen-Thorn et al. 2007). In addition, AO 0235+164 is one of the most highly polarized BL Lac objects known. During the outburst in 1983 January the optical polarization of the object varied from 12% to 24% over a 24 hr period (Smith 1996). Our polarimetric monitoring program has caught the source in a similar state, but with an even higher degree of polarization, $\gtrsim 30\%$. The polarimetric observations are enhanced by multicolor photometric measurements. Here we present the observations and show that the correlations we have uncovered provide strong evidence in support of the shock model.

2. OBSERVATIONAL DATA

Observational data at optical wavelengths (*BVRI* bands) were obtained at the 70 cm reflector of the Crimean Astrophysical Observatory with the photometer-polarimeter of the Astronomical Institute at St. Petersburg State University based on an ST-7 CCD. Methods of observation and data reduction of the photometric mode are described in detail in Hagen-Thorn et al. (2006). We used the comparison stars recommended by the Whole Earth Blazar Telescope (WEBT) program.⁵ The photometric errors do not exceed 0.03 mag in the *B* band and 0.02 mag in other bands when the object is brighter than 17 mag.

Observations at near-IR wavelengths (*JHK* bands) were carried out at the 1.1 m telescope of the Main (Pulkovo) Astronomical

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⁵ See <http://www.to.astro.it/blazars/webt>.

TABLE 1
OPTICAL DATA

MJD	<i>B</i>	MJD	<i>V</i>	MJD	<i>R</i>	MJD	<i>I</i>
27.3865.....	20.26 ± 0.17	27.3946	19.06 ± 0.05	27.3784	18.43 ± 0.03	27.3823	17.65 ± 0.03
28.3267.....	19.71 ± 0.17	28.3345	19.01 ± 0.07	28.3489	18.44 ± 0.04	28.3473	17.63 ± 0.03
29.3514.....	19.95 ± 0.17	29.3592	19.08 ± 0.05	29.3749	18.45 ± 0.04	29.3735	17.68 ± 0.03

NOTES.—Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content. MJD is JD −2,454,000.

Observatory of the Russian Academy of Sciences located at Campo Imperatore (Italy) and equipped with the SWIRCAM camera. Methods of reduction are the same as for the optical observations. Errors in *JHK* do not exceed 0.02 mag when the object is brighter than 16 mag in the *J* band. In all cases the calibration of Mead et al. (1990) was used to transform magnitudes to flux densities (subsequently referred to as “fluxes”).

Polarimetric observations were performed in the *R* band using two Savart plates rotated by 45° relative to each another. By swapping the plates, the observer can obtain either the relative Stokes *q* or *u* parameter from the two split images of each source in the field. Instrumental polarization was found via stars located near the object, under the assumption that their radiation is unpolarized. The Galactic latitude of AO 0235+164 is −39° so that interstellar polarization (ISP) in this direction is less than 0.7%. To correct for the ISP, the mean relative Stokes parameters of nearby stars were subtracted from the relative Stokes parameters of the object. This accounts for the instrumental polarization as well. The errors in degree of polarization are less than 2% for *R* < 16.5 mag, while the EVPA is determined with a precision of several degrees.

The results of photometric observations in the optical and IR bands are given in Tables 1 and 2, respectively. The light curves are shown in Figure 1 for the convenience of visual inspection. One can see that during the outburst the brightness increases by more than 3 mag. Table 3 lists the results of the polarimetric observations. In Figure 2 the top three panels illustrate the photometric *R* and polarimetric observations for three consecutive Julian dates during the most dramatic period of the outburst. Intraday variations (IDV) are evident within a given Julian date. The bottom three panels present absolute Stokes parameters during the same period. The existence of systematic variations during each night is a prominent feature of all the curves.

3. GLOBAL PROPERTIES OF VARIABILITY

3.1. Timescale of Variability

We have determined the timescale of variability of the flux in each band using the definition proposed by Burbidge et al. (1974): $\tau = dt/\ln(F_1/F_2)$, where *dt* is the time interval between flux measurements *F*₁ and *F*₂, with *F*₁ > *F*₂. We have calculated

all possible timescales τ_{ij} for any pair of observations for which $|F_i - F_j| > \sigma_{F_i} + \sigma_{F_j}$ at frequency ν . The minimum timescale at frequency ν is determined as $\tau_\nu = \min\{\tau_{ij,\nu}\}$, where $i = 1, \dots, N - 1, j = i + 1, \dots, N$, and *N* is the number of observations. Table 4 lists the results of these calculations as well as the timescale of the polarized flux variability. The uncertainties of the values of τ_ν are determined by errors of the flux measurements. However, the minimum timescale of variability that we derive is mainly constrained by the sampling; for example, the *B*, *V*, and *I* light curves have only two measurements during JD 2,454,077 (Table 1), the date at which we find the minimum timescales in the *R* band and at IR wavelengths. In Table 4 we enclose the timescales derived from these light curves in brackets to indicate that they cannot be compared with the timescales derived from the better sampled *R*, *J*, *H*, and *K* light curves.

The values of τ_ν indicate that during the event the timescale of variability was only a few hours and the shortest timescale, ~0.3 hr, occurred in the polarized flux. Comparison of the timescales of the total and polarized flux variability in the *R* band implies that the polarized emission originates in a subsection (~ $\frac{1}{5}$) of the optical emission region. Moreover, the light curves with similar sampling during the event (*R*, *J*, *H*, and *K* data) reveal an increase of timescale with wavelength.

3.2. Multicolor Behavior

We have calculated the discrete cross-correlation function (DCF) between the *R*-band light curve and light curves at other wavelengths using the approach suggested by Edelson & Krolik (1988) for unequally spaced data. The functions were computed for lags between light curves from −6 to +6 hr, with a step of 0.5 hr and with the constraint that at least five pairs of measurements are needed to define the coefficient of correlation at a given delay. Figure 3 presents the results of the calculations. The absence of points at some lags indicates that the data are not adequate to determine the DCF for such delays owing to the constraint.

Figure 3 shows that the DCFs have maxima at different delays between the light curves. The maxima are distinct only for the optical light curves and indicate that variations in the *B* band lead variations in the *R* band by ~0.5–1 hr, while variations in the *V* and *I* bands are simultaneous within 0.5 hr with the variability in

TABLE 2
NEAR-IR DATA

MJD	<i>J</i>	MJD	<i>H</i>	MJD	<i>K</i>
979.3865.....	17.24 ± 0.11	979.5627	16.45 ± 0.15	979.5666	15.31 ± 0.19
980.3267.....	17.25 ± 0.07	980.6206	16.32 ± 0.09	980.6258	15.47 ± 0.16
985.3514.....	17.27 ± 0.06	985.5778	16.19 ± 0.05	985.5828	15.70 ± 0.16

NOTE.—Table 2 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content. MJD is JD −2,453,000.

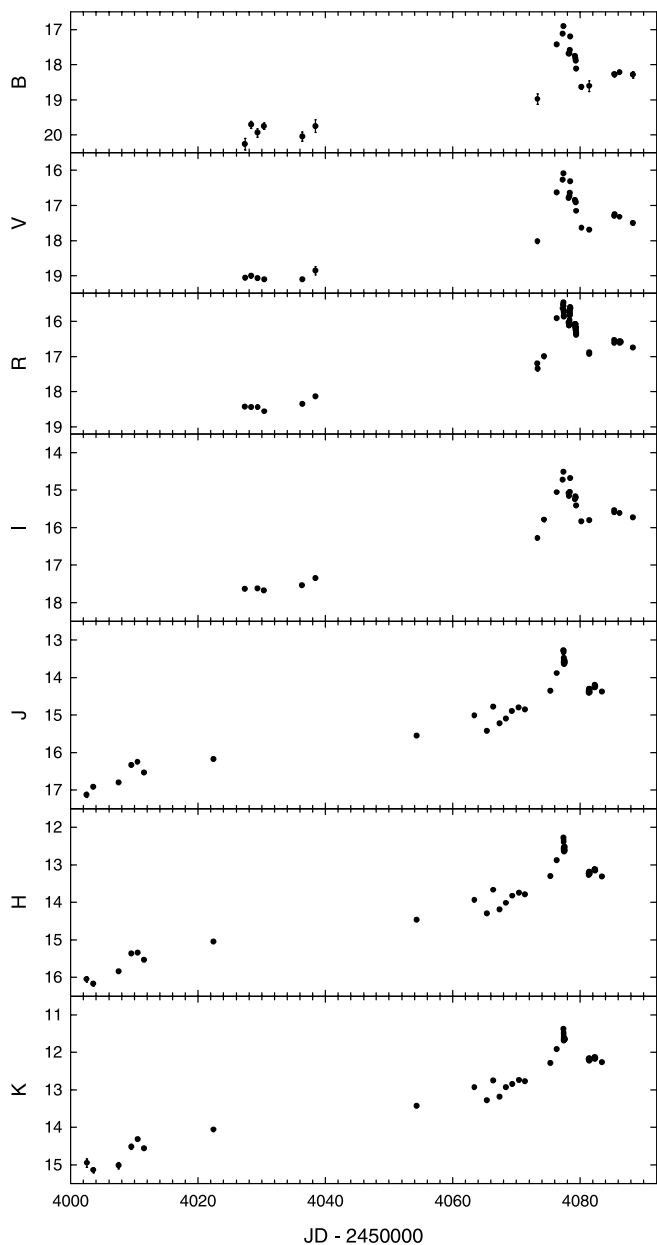


FIG. 1.—Light curves of AO 0235+16 in the optical and IR bands.

TABLE 3
POLARIZATION DATA IN THE *R* BAND

MJD (1)	P (%) (2)	Θ (deg) (3)
77.3307.....	32.7 ± 1.0	149.5 ± 0.8
77.4282.....	27.7 ± 1.4	152.2 ± 1.3
77.4433.....	25.9 ± 1.6	153.8 ± 1.8

NOTE.—Table 3 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content. Col. (1): JD $-2,454,000$; col. (2): degree of the polarization; col. (3): position angle of the polarization.

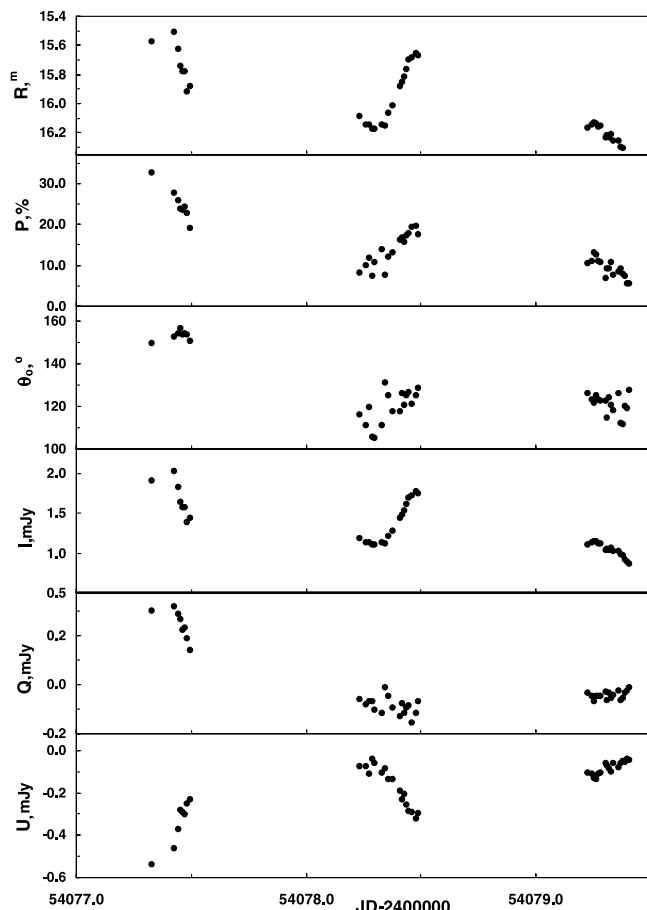


FIG. 2.—Simultaneous photometric and polarimetric data for AO 0235+16 at three consecutive Julian dates during the outburst.

the *R* band. Although the peaks of the DCFs for the near-IR light curves are broad and their positions are uncertain within 4–5 hr, the delay of variations in the near-IR region compared to those in the *R* band is statistically significant. The peaks of the DCF values and their delays for each light curve with respect to the *R*-band light curve are listed in Table 4. Such delays between the light curves are expected if the sizes of the emission regions at different wavelengths scale with the timescales of the variability found above.

3.3. Polarization Properties

Table 3 shows that very high degrees of polarization (up to 30%) were observed during the 2006 December outburst. Figure 4 demonstrates that the degree of polarization increased when the object brightened. This finding is confirmed by the high value of the DCF peak between the flux in the *R* band and the degree of polarization (Table 4). The DCF indicates also that the *R*-band and fractional polarization variations were simultaneous within 0.5 hr (Fig. 3). Figure 4 shows a wide range, $\sim 90^\circ$, of variability of the polarization position angle. However, Θ_0 aligns closely with the parsec jet direction, $\sim -15^\circ$ (Jorstad et al. 2001; Piner et al. 2006), when the degree of polarization exceeds 20%.

Visual inspection of Figure 2 reveals a correlation between Stokes parameters—between Q and I and between U and I —and varying behavior of the Stokes parameters from one epoch to another. The correlation coefficients calculated separately for

TABLE 4
MULTICOLOR PROPERTIES OF THE VARIABLE COMPONENT

Band (1)	$\log(\nu)$ (2)	N (3)	τ_{\min} (hr) (4)	DCF_{peak} (5)	Δt (hr) (6)	$\log(F_{\nu}/F_R)$ (7)
<i>B</i>	14.833	24	(5.27 ^{+1.36} _{-0.90})	0.89 ± 0.10	+1.0 ^{+0.5} ₋₁	-0.211 ± 0.012
<i>V</i>	14.736	24	(6.15 ^{+0.40} _{-0.34})	0.95 ± 0.11	0.0 ⁺¹ _{-0.5}	-0.120 ± 0.006
<i>R</i>	14.670	66	1.73 ^{+0.22} _{-0.29}	1.0	0.0	0.0
<i>I</i>	14.574	24	(4.81 ^{+0.29} _{-0.25})	0.85 ± 0.09	0.0 ⁺¹ _{-0.5}	0.142 ± 0.007
<i>J</i>	14.387	55	2.91 ^{+0.46} _{-0.34}	0.98 ± 0.02	-3.5 ^{+1.5} _{-2.5}	0.256 ± 0.007
<i>H</i>	14.262	55	2.19 ^{+0.55} _{-0.37}	0.98 ± 0.03	-3.5 ^{+1.5} _{-2.5}	0.400 ± 0.006
<i>K</i>	14.140	54	3.01 ^{+1.21} _{-0.67}	0.97 ± 0.03	-3.5 ^{+1.5} _{-2.5}	0.526 ± 0.005
<i>P</i>	14.670	54	0.31 ^{+0.04} _{-0.04}	0.74 ± 0.08	0.0 ⁺¹ _{-1.5}	...

NOTES.— Col. (1): filter of photometry, *P* corresponds to the polarization data; col. (2): logarithm of effective frequency of the filter; col. (3): number of observations; col. (4): minimum timescale of variability, unreliable values are enclosed in brackets; col. (5): peak of discrete cross-correlation function of the light curve at frequency ν with respect to the *R*-band light curve; in the case of polarization data the peak is given for the DCF between the *R* band and fractional polarization light curves; col. (6): delay of the peak; a plus sign means that the light curve at frequency ν leads the *R*-band light curve, while a minus sign is the opposite case; col. (7): logarithm of the contribution of the variable component in the SED at frequency ν relative to the contribution in the *R* band.

each Julian date, given in Table 5, confirm the tight correlation between the Stokes parameters.

4. PROPERTIES OF THE SOURCE RESPONSIBLE FOR VARIABILITY

4.1. Method of Analysis

Our current understanding of active galactic nuclei pictures an AGN as a complex system in which different components—the host galaxy, accretion disk, corona above the disk, broad-line regions, and jet—contribute to the total flux. In some cases multicolor photometric and polarimetric observations of variability may make it possible to derive the characteristics of the variable source (spectral energy distribution, SED, and polarization pa-

rameters) without knowledge of the absolute contribution of the other components to the total radiation.

Let us suppose that the variability within some time interval is due to a single variable component. If the variability is caused only by its flux variation, while the relative Stokes parameters q and u (for polarimetry) or relative SED (for photometry) remain unchanged, then in the space of absolute Stokes parameters $\{I, Q, U\}$ or in n -dimensional flux space $\{F_1, \dots, F_n\}$ (n is the number of spectral bands used in multicolor observations) the observational points must lie on straight lines. The slopes of these lines are relative Stokes parameters of the variable component (for polarimetry) or flux ratios for different pairs of bands as determined by its SED (for photometry).

With small caveats, the opposite is also true. In the case of photometry, a linear relation between observed fluxes in two different wavelengths during some period of flux variability implies that the flux ratio does not change. Such a relation for several bands indicates that the relative SED of the variable component

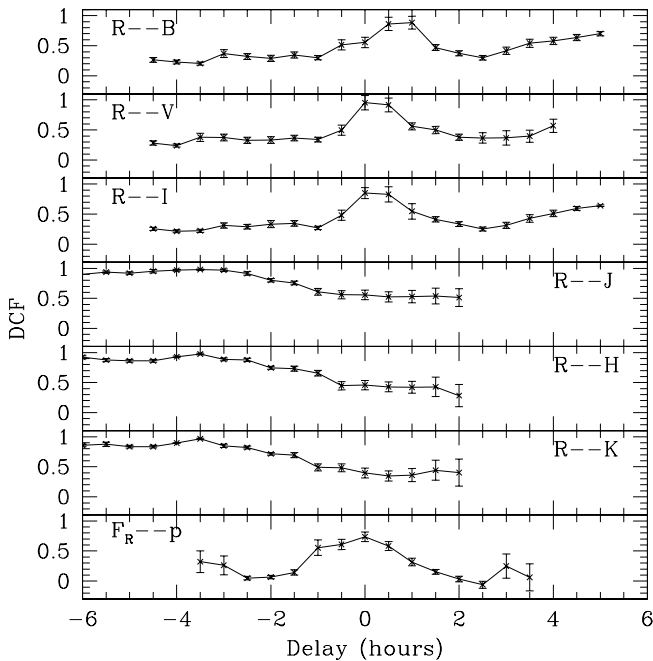


FIG. 3.— Discrete cross-correlation function between light curves in different bands with respect to the *R*-band light curve; a negative delay means that *R*-band variations lead. *Bottom panel*: DCF between degree of polarization and total flux density in the *R* band.

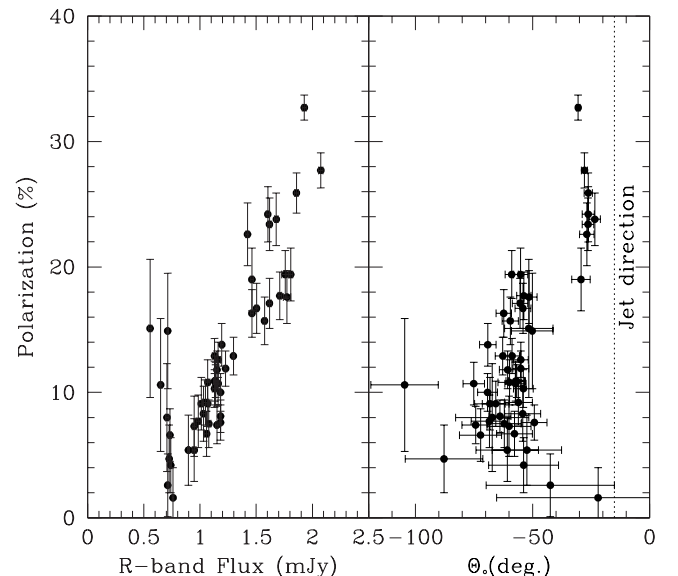


FIG. 4.— *Left*: Dependence between the degree of polarization and flux in the *R* band. *Right*: Dependence between the degree of polarization and polarization position angle; the dotted line indicates direction of the parsec scale jet.

TABLE 5
POLARIZATION PROPERTIES OF THE VARIABLE COMPONENT

MJD (1)	r_{QI} (2)	r_{UI} (3)	p_{var} (%) (4)	Θ_{var} (deg) (5)
77.447.....	0.93	-0.90	50.0 ± 9.4	-30.4 ± 5.4
78.373.....	-0.48	-0.98	36.7 ± 3.4	-49.8 ± 2.7
79.320.....	-0.58	-0.92	33.1 ± 5.2	-53.9 ± 4.5

NOTES.—Col. (1): JD $-2,454,000$; col. (2): correlation coefficient between Stokes parameters Q and I ; col. (3): correlation coefficient between Stokes parameters U and I ; col. (4): degree of polarization; col. (5): position angle of polarization.

remains steady and can be derived from the slopes of the lines. In the case of polarimetry, a linear relation between observed Stokes parameters suggests that the variable component has a constant degree of polarization and polarization position angle, the values of which can be obtained from the relative Stokes parameters q and u that correspond to the slope of the Q versus I and U versus I lines, respectively. Further details of the method of analysis are provided in Hagen-Thorn & Marchenko (1999).

4.2. Polarization Parameters of the Variable Component

Correlation plots of the absolute Stokes parameters for three consecutive epochs during the outburst (JD 2,454,077, 2,454,078, and 2,454,079) are given in Figures 5a, 5b, and 5c, respectively. One can see that in all cases the points lie on straight lines, which leads us to conclude that during a given epoch the relative Stokes parameters of the variable component remained unchanged. The slopes of the straight lines in Figure 5 are determined by the orthogonal regression method. They give the relative Stokes parameters q_{var} and u_{var} of the variable component that we use to calculate its degree and position angle of polarization, p_{var} and Θ_{var} (Table 5). Table 5 indicates that the degree of polarization of the variable component is very high and decreases from 50% to 30% as the object fades. This is accompanied by a systematic variation of the polarization direction. At the highest degree of polarization the EVPA tends to align to within 15° with the direction of the parsec-scale jet inferred from the VLBI maps of AO 0235+164 (Jorstad et al. 2001; Piner et al. 2006).

4.3. Spectral Energy Distribution of the Variable Component

We compare the fluxes in different bands relative to the R and J fluxes for the optical and near-IR data, respectively (see Fig. 6), since these two bands have the largest number of observations. According to Figure 2, the data reveal intraday variability, which can affect the flux-flux comparison because the measurements are not completely simultaneous. For example, during Julian dates with intensive monitoring, delays of ~ 10 – 15 minutes between observations in different bands occur. For such epochs the fluxes in the R band were interpolated to the corresponding times of the B -, V -, and I -band measurements (the same is true for the J band with respect to the H and K bands). For epochs with a few measurements, the average at each band was used.

The slopes of the lines were derived using the orthogonal regression method. They are corrected for extinction based on the information provided by Raiteri et al. (2005). The logarithms of the corrected values are listed in Table 4. Using these values, we have constructed SEDs in the optical and near-IR regions as well as the combined SED (via the flux-flux diagram for R and J) for the whole range from the B to K band (Fig. 7). Figure 7 shows

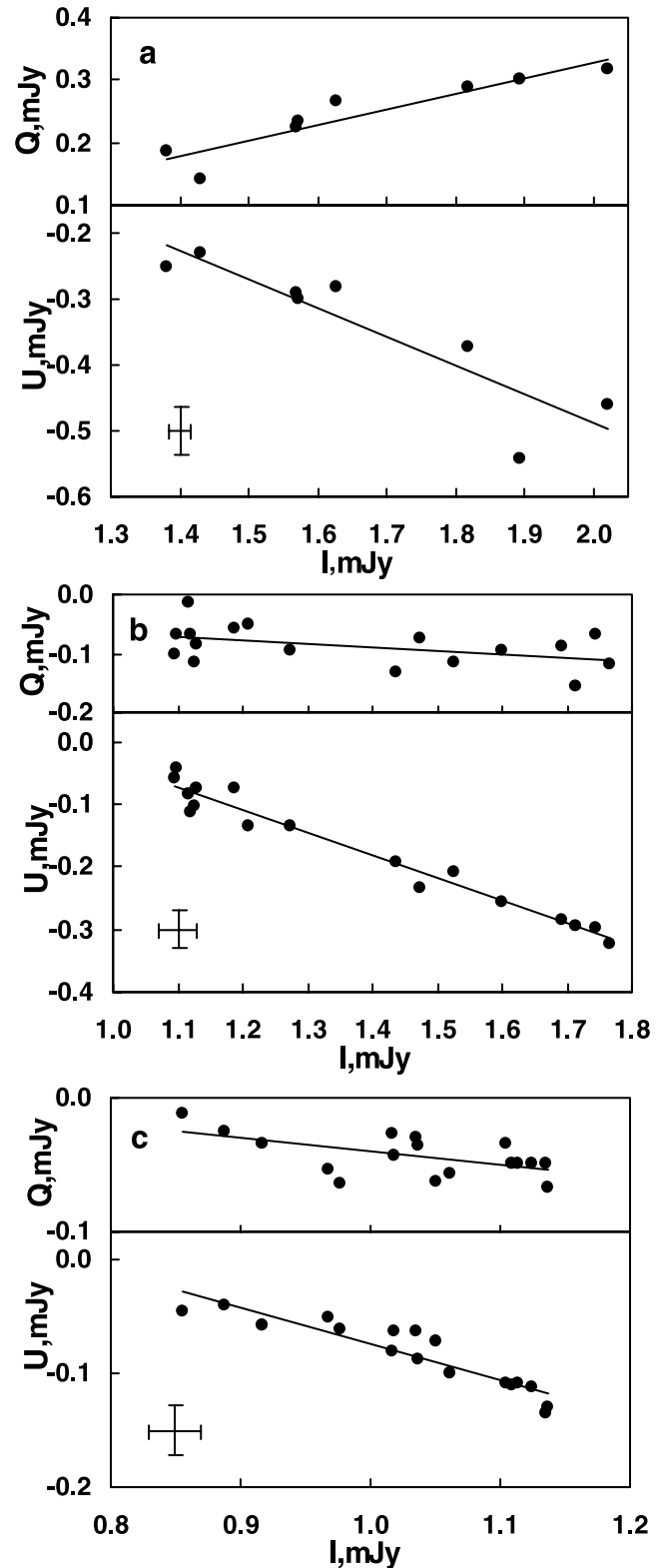


FIG. 5.—Comparison of absolute Stokes parameters for three consecutive Julian dates during the outburst: (a) $-2,454,077$; (b) $-2,454,078$; (c) $-2,454,079$. Crosses correspond to the uncertainties of the parameters.

that the spectra can be represented by a power law, $F_\nu \sim \nu^{-\alpha}$, where α is the spectral index. In the near-IR region $\alpha = 1.10 \pm 0.03$, while in the optical region $\alpha = 1.39 \pm 0.12$. Although there appears to be a slight steepening of the spectrum in the optical region, this falls within the 2σ uncertainty, so that the

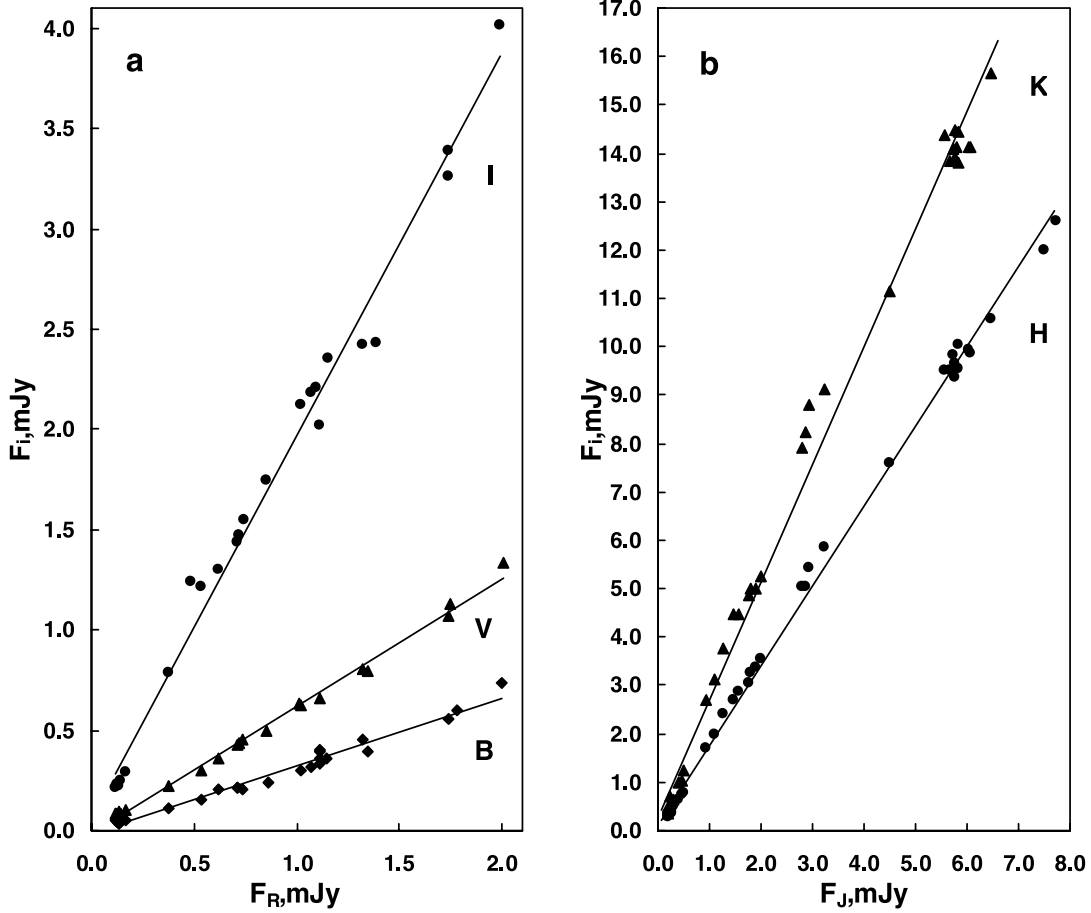


FIG. 6.—Flux-flux diagrams for (a) optical and (b) IR wavelengths.

combined SED can be fit by a single power law with $\alpha = 1.04 \pm 0.06$. This result indicates that the same component with the relative SED shown in Figure 7 is responsible for the source variability in the whole range from the *B* to *K* band.

5. DISCUSSION

The results of the polarimetric and photometric observations show that the dramatic variability seen in AO 0235+164 in 2006 December might be explained by a single variable component possessing the following properties: (1) a steady spectral shape; (2) an increase in the size of the emitting region with wavelength; (3) a very high degree of polarization, up to 50%; (4) a strong correlation between the degree of polarization and flux; and (5) a tendency of the magnetic field at the highest polarization state to be perpendicular to the inner radio jet direction. These properties are characteristics of the model that describes an outburst in a blazar as a transverse shock propagating down a relativistic jet with a turbulent magnetic field (Marscher & Gear 1985; Hughes et al. 1985; Marscher 1996). The timescale of variability relates to the thickness of the shock front, which is determined by the lifetime of relativistic electrons accelerated at the front. This thickness decreases with frequency owing to synchrotron radiation losses. The shock orders the turbulent magnetic field along the front, which is perpendicular to the jet direction.

We consider a model of a square-wave transverse shock moving through a turbulent plasma with a constant Lorentz factor, Γ . The size and shape of the emission region at a given frequency are

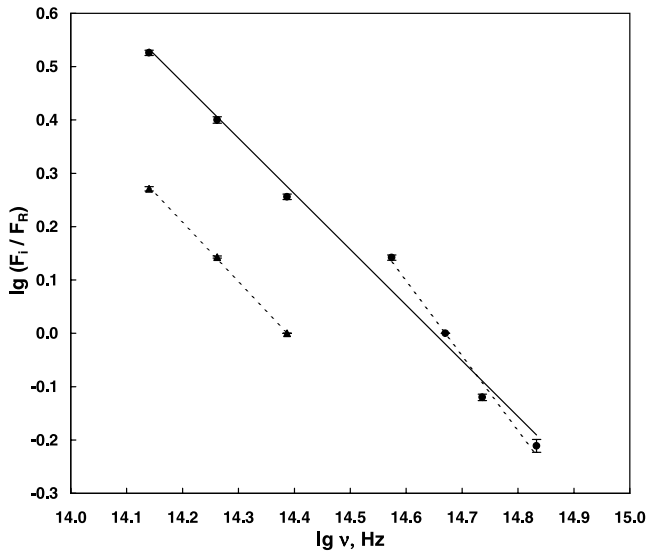


FIG. 7.—Relative SEDs at IR and optical wavelengths (*dashed lines*) and for the combined spectrum (*solid line*). The optical SED is relative to the *R*-band flux. The IR SED is relative to the *J*-band flux. The combined SED is constructed using a linear dependence between simultaneous observations in the *J* and *R* bands.

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