MULTIBAND OPTICAL POLARIMETRY OF THE BL LACERTAE OBJECT PKS 2155—304: INTRANIGHT AND LONG-TERM VARIABILITY

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ABSTRACT

The polarized and total flux of the BL Lac object PKS 2155—304 were monitored intensively and simultaneously in the optical UBVRI bands with the Turin photopolarimeter at the CASLEO 2.15 m telescope during four campaigns in 1998 June, August, and November and 1999 August. The effective observation time amounted to ~47 hr. PKS 2155—304 showed a linear polarization percentage (P) usually ranging between 3% and 7% and a polarization position angle (P.A.) mainly between 70° and 120°. The highest temporal resolution of our observations, 15 minutes, is unprecedented for polarimetric monitoring of this source and has allowed us to detect amplitude variations of the linear polarization percentage from 6% to 7.5% in timescales of hours. In some nights the polarization percentage seems to increase toward shorter wavelengths; however, the polarized spectrum does not vary significantly with time. The most remarkable variability event occurred on 1998 June 18, when the degree of linear polarization decreased by more than a factor 2 in 1 day in all bands, while the P.A. rotated by 90°. This is consistent with the presence of two emission components, of different polarization degree and position angle. Intranight variability of P and P.A. can be interpreted with small-amplitude physical or geometrical changes within the jet. Measurements of the circular polarization over time intervals of days set upper limits of 0.2%. Simultaneous photometry taken with the Turin Photopolarimeter and with a CCD camera at Córdoba Astronomical Observatory did not show light variations correlated with those of the linearly polarized flux.

Subject headings: BL Lacertae objects: individual (PKS 2155—304) — galaxies: active — galaxies: photometry — polarization

1. INTRODUCTION

Relativistic jets are thought to characterize the geometry of the most powerful extragalactic sources, blazars and gamma-ray bursts (GRBs). In both classes of sources, synchrotron radiation is responsible for the spectrum production over up to 10 decades of energy, from radio to soft gamma-rays. Linear polarization, seen in blazars at a level of 1% to 30% (Angel & Stockman 1980; Takalo 1991; Takalo et al. 1992; Visvanathan & Wills 1998) and recently detected also in the optical afterglow of two GRBs (Covino et al. 1999; Wijers et al. 1999; Rol et al. 2000), is the most compelling indication of synchrotron radiation. Relativistic beaming enhances the polarized nonthermal jet radiation with respect to the unpolarized emission of the host galaxy, resulting in a high net polarization percentage. Therefore, short timescale variations of the polarized light trace the dynamics of the plasma inside the jet, and their monitoring yields the most direct insight into the jet physics and powering source.

Studies of linear polarization of blazars have been conducted from radio to UV wavelengths (Saikia & Salter 1988; Gabuzda, Sitko, & Smith 1996; Allen et al. 1993) and optical polarization level has been also adopted as a characteristic feature to select blazar sources (Borra & Corriveau 1984; Impey & Tapia 1988; Jannuzi, Green, & French 1984; Jannuzi, Smith, & Elston 1984; Allen et al. 1993; Jannuzi et al. 1993b; Smith & Sitko 1991; Smith et al. 1993b; Fleming et al. 1993; Jannuzi, Green, & French 1993a). However, variability of polarization of blazars is poorly investigated, and rapid and intensive monitoring campaigns, even of the brightest and mostly polarized sources, are largely lacking, except for S5 0716+714 (Impey et al. 2000).

The BL Lac object PKS 2155—304 is a nearby blazar (z = 0.116; see Falomo, Pesce, & Treves 1993), one of the brightest at optical to X-ray frequencies, and its polarized optical light has been observed over many years by Brindle et al. (1986), Mead et al. (1990), Smith & Sitko (1991), Smith et al. (1992), Allen et al. (1993), Jannuzi et al. (1993b), Cour-
voisier et al. (1995), and Pesce et al. (1997). The main results are a polarization fraction $P$ varying from 2% to 10%, a position angle P.A. preferentially oriented at about 100°–120°, and a wavelength dependence of polarization (WDP) tending to be null or slightly increasing toward the blue. Observations of UV polarization with Hubble Space Telescope (HST) by Allen et al. (1993) yielded $P = 3\%$ and P.A. = 101° and confirmed a positive WDP (i.e., P decreasing toward longer wavelengths) through the whole optical–UV range. Since in PKS 2155–304 the synchrotron mechanism is responsible for the spectrum up to hard X-rays, producing a spectral maximum at UV/soft X-rays (“blue blazars”; see Padovani & Giommi 1995 and Fossati et al. 1998), correlation is expected of flux variations from optical to X-ray wavelengths. This was observed in past multiwavelength campaigns (Edelson et al. 1995; Urry et al. 1997). In particular, in 1994 May, the polarized optical light variations were faster than those of the total light and were better correlated with the UV variations. This indicates that optical polarization is an efficient tracer of synchrotron emission, and its variations probe, in the most detailed way, the energy production processes.

To explore variability of the polarization with timescales from months down to less than an hour, we conducted four campaigns of polarimetric monitoring of PKS 2155–304 during 1998 and 1999 at the 2.15 m telescope of the Complejo Astronomico El Leoncito (CASLEO, Argentina). Linear and circular polarization data along with photometric data have been collected simultaneously in $UBVRI$ bands with a maximum temporal resolution of 15 minutes.

A description of the observations and data reduction process is given in § 2, while § 3 is devoted to the presentation of the photometric and polarimetric results. In § 4 we compare our findings with the historical polarization behavior of PKS 2155–304 and discuss them in § 5. Preliminary and partial results were presented in Treves et al. (1999).

2. OBSERVATIONS

2.1. Polarimetry

The polarimetric data in the $UBVRI$ bands were gathered during four campaigns conducted at the CASLEO 2.15 m telescope equipped with the Photopolarimeter of the Turin Observatory, for a total of about 47 hr on source exposure time. A log of all the observations is shown in Table 1.

The instrument is a double-channel chopping photopolarimeter (Scaltriti et al. 1989), based on the design sketched by Pirola (1973). A half-wave or quarter-wave retarder plate (for linear or circular polarimetry, respectively) is inserted into the light beam coming from the telescope. The plate is rotated through eight positions by 22.5° steps to explore polarization of incoming light. A subsequent calcite slab splits the light into ordinary and extraordinary rays, with orthogonal polarization planes. These two rays are alternatively selected by a rotating chopper; afterward, they pass through a pair of identical diaphragms. In passing through the calcite slab, the extraordinary/ordinary component from the sky is refactored on the ordinary/extraordinary component from the (object + sky). Thus both components from the sky pass both diaphragms, and polarization of the sky is eliminated. Finally, the light is split by four dichroic plus bandpass filter combinations and sent to five photomultiplier tubes. The response of each of the five channels corresponds to one of the $UBVRI$ bands. In this way, truly multicolor simultaneous photometry and polarimetry is obtained. It can be noticed that the image is focused on the diaphragm wheel. So the light beam incident on the retarder plate is converging at an angle of about 3°, taking into account the focal ratio of the telescope. The two light beams (ordinary and extraordinary) then become parallel by means of a couple of lenses before reaching the dichroic filters. An integration time of 10 s for each retarder plate position was chosen for all observations, giving a final maximum time resolution of about 3.5 minutes. However, in order to get an acceptable signal-to-noise ratio, the measurements have been binned with four or eight plate cycles bins (approximately 15 or 30 minutes) according to the different quality of data in the various nights. For all the observations a 15.8° diameter diaphragm was used. The determination of the instrumental polarization and orientation of zero point of the retarder with respect to north is performed with the repeated observation of null and high-polarization standard stars, respectively.

The uncertainties affecting our average measures of instrumental polarization range typically between 0.16% and 0.36% in the $U$ band, and between 0.02% and 0.09% in the other bands. The position angle corresponding to the zero point is typically 79°8–82°6 with respect to north.

Data analysis is performed by dedicated routines. They allow calculation of polarization and position angle from the eight integrations made in different orientations of the retarder plate. Error estimates are obtained both from photon statistics and least-squares fits to the eight integrations. The sky background level, measured at the beginning of each set of four cycles of full rotations of the retarder (each cycle being constituted by eight steps of 22.5°), is taken into account interpolating between sky measurements if the observed object (or the diaphragm) has not been changed; otherwise, the first background value is used. The averaging procedure uses weights determined from the inverse square of the estimated error for each observation. The error estimate is taken either from the least-squares fit of the double cosine curves to the eight integrations in the different positions of the retarder or from the photon statistics, whichever is greater. This prevents weights from having values larger than the theoretical maximum corresponding to photon noise limit, which could happen if only the least-squares fits with only eight data points in each observation were relied upon. The uncertainties affecting our average measures of instrumental polarization range typically between 0.02% and 0.1% (the largest values being recorded in $U$ and $I$ bands). These systematic uncertainties affect the measurements of the polarization percentage of the observed source by 0.07% in the $U$ band, 0.04% in $B$, 0.02% in $V$, 0.03% in $R$, and 0.05% in $I$. The systematic error on the orientation of the zero position of the retarder is estimated to be about 0.5°, which leads to an uncertainty of about 0.01% in the polarization percentage and about 1° in the position angle of PKS 2155–304. We also checked the repeatability of the measurements of $P$ and P.A. of standard stars from night to night. The scatter on P.A. values is less than 1°, while the scatter in $P$ is of the order of 0.02% in all bands. Systematic errors are much smaller than statistical errors and therefore
### Table 1

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| Date          | JD*          | On-Source Integration Time (minutes) | Polarization State | Filter | P (%)      | P.A. (deg) |
|---------------|--------------|------------------------------------|-------------------|--------|------------|------------|
| 1998 Jun 17   | 2,450,982.726 | 150                                | l                 | U      | 4.76 (0.50)| 93.1 (3.9) |
|               | 2,450,982.920 |                                    |                   | B      | 4.43 (0.51)| 96.4 (2.9) |
|               |              |                                    |                   | V      | 4.19 (0.41)| 96.7 (2.7) |
|               |              |                                    |                   | R      | 4.21 (0.35)| 97.1 (2.7) |
|               |              |                                    |                   | I      | 4.10 (0.66)| 96.5 (4.6) |
| 1998 Jun 18   | 2,450,983.767 | 75                                 | l                 | U      | 2.04 (0.38)| 12.0 (5.8) |
|               | 2,450,983.870 |                                    |                   | B      | 1.72 (0.36)| 4.3 (7.4)  |
|               |              |                                    |                   | V      | 1.81 (0.30)| 6.4 (3.8)  |
|               |              |                                    |                   | R      | 1.76 (0.25)| 8.6 (3.7)  |
|               |              |                                    |                   | I      | 1.42 (0.54)| 8.3 (11.3) |
| 1998 Jun 19   | 2,450,984.777 | 150                                | l                 | U      | 4.58 (0.40)| 101.3 (3.0) |
|               | 2,450,984.922 |                                    |                   | B      | 4.12 (0.51)| 104.1 (3.9) |
|               |              |                                    |                   | V      | 3.86 (0.25)| 102.4 (2.0) |
|               |              |                                    |                   | R      | 3.84 (0.25)| 101.5 (2.3) |
|               |              |                                    |                   | I      | 3.59 (0.50)| 101.0 (3.4) |
| 1998 Jun 20   | 2,450,985.751 | 120                                | l                 | U      | 5.70 (1.29)| 118.8 (6.0) |
|               | 2,450,985.904 |                                    |                   | B      | 5.06 (0.51)| 121.6 (3.1) |
|               |              |                                    |                   | V      | 4.37 (0.55)| 120.9 (2.9) |
|               |              |                                    |                   | R      | 4.46 (0.60)| 120.5 (3.4) |
|               |              |                                    |                   | I      | 4.04 (0.96)| 121.1 (5.9) |
| 1998 Jun 21   | 2,450,986.791 | 135                                | l                 | U      | 3.58 (0.43)| 125.4 (4.0) |
|               | 2,450,986.926 |                                    |                   | B      | 3.29 (0.47)| 130.1 (3.2) |
|               |              |                                    |                   | V      | 3.13 (0.21)| 131.5 (1.6) |
|               |              |                                    |                   | R      | 3.16 (0.29)| 131.3 (3.0) |
|               |              |                                    |                   | I      | 3.13 (0.60)| 129.6 (4.7) |
| 1998 Jun 22   | 2,450,987.60  | 75                                 | l                 | U      | 4.44 (0.72)| 115.9 (4.6) |
|               | 2,450,987.833 |                                    |                   | B      | 3.98 (0.50)| 119.1 (3.3) |
|               |              |                                    |                   | V      | 3.41 (0.31)| 119.4 (2.6) |
|               |              |                                    |                   | R      | 3.29 (0.20)| 120.1 (1.8) |
|               |              |                                    |                   | I      | 2.83 (0.79)| 120.0 (7.7) |
| 1998 Aug 26   | 2,451,052.516 | 345                                | l                 | U      | 6.15 (0.93)| 68.9 (4.4)  |
|               | 2,451,052.816 |                                    |                   | B      | 6.12 (0.68)| 68.2 (3.2)  |
|               |              |                                    |                   | V      | 5.64 (0.58)| 69.4 (2.8)  |
|               |              |                                    |                   | R      | 5.44 (0.36)| 69.5 (1.8)  |
|               |              |                                    |                   | I      | 5.24 (0.69)| 70.1 (3.8)  |
| 1998 Aug 27   | 2,451,053.590 | 240                                | l                 | U      | 6.12 (0.54)| 69.1 (2.5)  |
|               | 2,451,053.836 |                                    |                   | B      | 5.93 (0.73)| 70.3 (3.6)  |
|               |              |                                    |                   | V      | 5.47 (0.39)| 72.4 (2.1)  |
|               |              |                                    |                   | R      | 5.43 (0.32)| 72.5 (1.7)  |
|               |              |                                    |                   | I      | 5.30 (0.64)| 73.7 (3.3)  |
| 1998 Aug 28   | 2,451,054.562 | 330                                | l                 | U      | 7.03 (0.52)| 63.1 (2.2)  |
|               | 2,451,054.808 |                                    |                   | B      | 6.82 (0.44)| 64.5 (1.9)  |
|               |              |                                    |                   | V      | 6.26 (0.34)| 66.7 (1.6)  |
|               |              |                                    |                   | R      | 6.16 (0.29)| 67.0 (1.3)  |
|               |              |                                    |                   | I      | 6.04 (0.47)| 67.7 (2.5)  |
| 1998 Nov 15   | 2,451,133.527 | 22                                 | c                 | U      | 0.19 (0.16)| ...         |
|               | 2,451,133.539 |                                    |                   | B      | 0.12 (0.08)| ...         |
|               |              |                                    |                   | V      | -0.07 (0.05)| ...       |
|               |              |                                    |                   | R      | -0.02 (0.08)| ...       |
|               |              |                                    |                   | I      | 0.04 (0.09)| ...         |
| 1998 Nov 16   | 2,451,134.547 | 15                                 | c                 | U      | -0.08 (0.10)| ...        |
|               | 2,451,134.555 |                                    |                   | B      | 0.25 (0.11)| ...        |
|               |              |                                    |                   | V      | -0.10 (0.07)| ...       |
|               |              |                                    |                   | R      | -0.10 (0.05)| ...       |
|               |              |                                    |                   | I      | -0.05 (0.11)| ...        |
| 1998 Nov 18   | 2,451,136.547 | 15                                 | c                 | U      | -0.04 (0.08)| ...        |
|               | 2,451,136.555 |                                    |                   | B      | 0.17 (0.11)| ...        |
|               |              |                                    |                   | V      | 0.13 (0.05)| ...        |
|               |              |                                    |                   | R      | 0.02 (0.05)| ...        |
|               |              |                                    |                   | I      | -0.14 (0.10)| ...        |
| 1998 Nov 19   | 2,451,137.551 | 15                                 | c                 | U      | -0.20 (0.08)| ...        |
|               | 2,451,137.558 |                                    |                   | B      | -0.32 (0.13)| ...        |
|               |              |                                    |                   | V      | -0.15 (0.05)| ...        |
|               |              |                                    |                   | R      | -0.07 (0.05)| ...        |
have been ignored in the following. Our reduction routines also account for the depolarization due to the instrumental setup (telescope + polarimeter). To estimate the efficiency of 100% polarized light detection, we used all the observations of highly polarized standards carried out at CASLEO from 1994 to 1997. An average correcting factor $1.03^{+0.04}$ was found to be necessary to reproduce the cataloged values in all bands from the measured ones and has been introduced in the reduction routines.

In Table 1 and in Figure 1 we report $P$ and P.A. averaged over each night for all campaigns. Uncertainties on the data points given in parentheses are the maximum between the statistical error associated with the individual points and the standard deviation within the night, in the specified photometric band. Only for the night of 1999 August 4, owing to the poor weather conditions resulting in low signal-to-noise ratio, all the collected data have been averaged without binning over the plate cycles, resulting in the weighted means and statistical errors that are reported in Table 1. Similar reduction has been performed also on circular polarimetry data. The resulting nightly means are reported in Table 1 along with statistical uncertainties.

### 2.2. Photometry

Photometry from CASLEO observations can be derived, from the same polarimetric data, by adding counts from ordinary and extraordinary rays for each plate position to obtain the total flux from the source, measured in the five $UBVRI$ bands. In order to correct the source flux for sky transparency or atmospheric extinction variations during the integrations, we observed reference stars 2 and 3 of Smith, Jannuzi, & Elston (1991) many times per night during the runs of 1998 June and August and 1999 August. However, photometry is much more sensitive than polarimetry to the sky conditions; therefore, meaningful magnitude measurements have been obtained only for the clearest nights or intervals. Table 2 shows a summary of the results.

To overcome partially the limitation inherent to the CASLEO photometry, on 1998 August 25–28 and 1999 August 1–5 we performed additional differential photometry in the $BVRI$ bands at the 1.54 m telescope located at Bosque Alegre Astrophysical Station of the Córdoba Astronomical Observatory (Argentina) equipped with a Photometrics 1024×1025 pixels CCD camera (Multi-functional Integral Field Spectrograph; Diaz et al. 1997, 1999). The magnitudes of PKS 2155–304 and of the standard stars labeled as 2 and 3 by Smith et al. (1991) were determined by means of aperture photometry routines in the MIDAS package. A circle with a diameter of 11.4” was used to measure BL Lac flux. The magnitude differences measured between the two standard stars are very close to the standard ones; this supports the similarity between the instrumental and the standard systems. Hence, standard magnitudes of PKS 2155–304 were calculated by assuming

### Table 1—Continued

| Date       | JD*               | On-Source Integration Time (minutes) | P.A. | Filter | $P$ (%) | P.A. (deg) |
|------------|-------------------|-------------------------------------|------|--------|---------|------------|
| 1999 Aug 1 | 2,451,392.594     | 270                                 |      | I      | -0.19 (0.10) | ...         |
|            | 2,451,392.828     |                                     |      | U      | 4.88 (1.23)  | 113.8 (7.3) |
|            |                   |                                     |      | B      | 5.64 (1.13)  | 113.7 (5.7) |
|            |                   |                                     |      | V      | 5.41 (0.95)  | 116.6 (4.9) |
|            |                   |                                     |      | R      | 5.34 (0.89)  | 115.9 (4.7) |
| 1999 Aug 2 | 2,451,393.570     | 285                                 |      | I      | 5.18 (0.97)  | 117.1 (5.3) |
|            | 2,451,393.820     |                                     |      | U      | 5.70 (0.51)  | 105.0 (2.6) |
|            |                   |                                     |      | B      | 5.71 (0.39)  | 105.7 (2.5) |
|            |                   |                                     |      | V      | 5.46 (0.31)  | 105.6 (1.8) |
|            |                   |                                     |      | R      | 5.53 (0.23)  | 106.1 (1.3) |
| 1999 Aug 3 | 2,451,394.566     | 300                                 |      | I      | 5.33 (0.55)  | 106.0 (3.0) |
|            | 2,451,394.820     |                                     |      | U      | 3.68 (0.46)  | 109.8 (3.5) |
|            |                   |                                     |      | B      | 3.70 (0.57)  | 110.4 (4.3) |
|            |                   |                                     |      | V      | 3.88 (0.33)  | 109.3 (2.4) |
|            |                   |                                     |      | R      | 3.76 (0.26)  | 108.1 (2.1) |
| 1999 Aug 4 | 2,451,395.574     | 285                                 |      | I      | 4.04 (0.86)  | 107.8 (5.8) |
|            | 2,451,395.918     |                                     |      | U      | 1.26 (0.14)  | 97.5 (3.1)  |
|            |                   |                                     |      | B      | 1.25 (0.21)  | 88.3 (4.8)  |
|            |                   |                                     |      | V      | 1.46 (0.14)  | 96.4 (2.8)  |
|            |                   |                                     |      | R      | 1.62 (0.14)  | 95.5 (2.5)  |
| 1999 Aug 4 | 2,451,395.676     | 60                                  |      | I      | 1.66 (0.25)  | 99.3 (4.3)  |
|            | 2,451,395.715     |                                     |      | U      | 1.05 (0.06)  | ...          |
|            |                   |                                     |      | B      | 0.01 (0.10)  | ...          |
|            |                   |                                     |      | V      | -0.15 (0.05) | ...          |
|            |                   |                                     |      | R      | 0.08 (0.03)  | ...          |
| 1999 Aug 5 | 2,451,396.703     | 75                                  |      | I      | 3.35 (1.29)  | 92.9 (6.9)  |
|            | 2,451,396.762     |                                     |      | U      | 4.34 (0.32)  | 91.8 (3.8)  |
|            |                   |                                     |      | B      | 4.31 (0.56)  | 94.3 (5.3)  |
|            |                   |                                     |      | V      | 4.03 (1.13)  | 95.3 (8.5)  |
|            |                   |                                     |      | R      | 4.14 (0.73)  | 95.6 (5.6)  |

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* JD at the first and last measurement of each night.

* I = linear polarization; c = circular polarization.
Figs. 1.—Nightly mean values of $P$ (left-hand panels) and P.A. (right-hand panels) in $UBVRI$ band during (a) 1998 June 17–22, (b) 1998 August 26–28, and (c) 1999 August 1–5 campaigns. Horizontal bars represent the duration of the observing run during each night. The dashed curves connecting the points are meant only to guide the eye.

$B = 12.73$, $V = 12.04$, $R = 11.64$, and $I = 11.28$ for the standard star 2, as reported by Smith et al. (1991). Nightly means are shown as a summary in Table 2.

3. RESULTS

3.1. Linear Polarization

The linear polarization percentage was roughly at the same average level in all bands in 1998 June and 1999 August, while it was $\sim 1.3$–1.5 times higher in 1998 August (see Table 1). Correspondingly, the polarization angle was around $100^\circ$–$120^\circ$ in 1998 June and 1999 August and at $70^\circ$ in 1998 August (Fig. 1). Day-to-day variations generally did not exceed a factor $\sim 1.2$ in amplitude for $P$ and $\sim 20^\circ$ in P.A., with the exception of a relevant variability episode on 1998 June 18: the polarization decreased in all bands (the largest variation was from 4% to 1.5% in $I$ band) in no more than 21 hr and subsequently returned in 22 hr to the value it had before the “dip” (Fig. 1a). Although a precise determination of the halving and doubling timescales of this variation is hampered by the daytime gap, based on the modest decreasing trend present in all bands during the night of June 17 (see Fig. 2a) we estimate that the halving/doubling timescale could be as short as 14 hr. Simultaneously, the polarization plane rotated by about $90^\circ$. Following our standard procedure, during the 1998 June run, we observed several high-polarization standard stars; some of them were monitored each night. Their position angles show constant values in all the nights with a maximum deviation of $\sim 1^\circ$. We are therefore confident that the behavior of PKS 2155–304 cannot be attributed to a systematic instrumental effect. A hint of a similar variability episode is contained in the 1999 August data, when the polarization decreased from 5.5% to 1.5% in the $V$ band.
bands. The event recorded during 1998 August 28 (see Fig. 2) is particularly notable for smoothness of the temporal profile. After a small decrease in polarization in the first 15 minutes to a low state, maintained for about one-half hour, in the next 2 hr the source exhibits a regular and rather smooth increase up to 1.2 times the minimum value. During over 2 days, while no simultaneous rotation of the P.A. was recorded. However, owing to the poor quality of the sky in these nights, this event should be considered with some caution.

Intrannight variations of up to a factor ~1.3 in $P$ and ~7° in P.A. are sometimes detected with timescales of a few hours. These are either random, or they follow the longer timescale trends (as in the night of 1998 June 17, where the long time trend is prevailing). Data from the three nights in which such variations are more apparent (one for each campaign) are plotted for selected bands in Figure 2. In the same nights, similar behaviors are recorded also in the other bands. The event recorded during 1998 August 28 (see Fig. 2b) is particularly notable for smoothness of the temporal profile. After a small decrease in polarization in the first 15 minutes to a low state, maintained for about one-half hour, in the next 2 hr the source exhibits a regular and rather smooth increase up to 1.2 times the minimum value. During other nights, the variations detected over similar timescales are more modest or absent.

We searched for a correlation between polarization and position angle on various timescales. In some nights there is evidence of such a correlation, while in other cases the variations in $P$ and P.A. seem little correlated (Fig. 3). Moreover, within the same night, the $P$-P.A. correlation may be different in the five photometric bands. Looking at intrannight variations, a correlation can be evidenced only for the dip of 1998 June 18 (Fig. 1a). Finally, looking at the whole data set (see Table 1), there is a suggestion of a correlation between subsequent campaigns, in the sense of increasing $P$ and decreasing P.A. from 1998 June to August and vice versa from 1998 August to 1999 August.

3.2. Wavelength Dependence of Polarization

We also investigated the wavelength dependence of polarization (WDP). Examples from selected nights are in Figure 4. Non-null WDP was found in some nights during the runs of 1998 June and August, in the sense of decreasing polarization with increasing wavelength. This dependence disappeared in the run of 1999 August, when the polarized spectrum appears flat. Following Smith & Sitko (1991), we

## Table 2

| Date            | $m_b$ | $m_r$ | $m_i$ |
|-----------------|-------|-------|-------|
| 1998 Jun 17     | 13.03 | 13.45 | 13.09 |
|                 | (0.02) | (0.04) | (0.03) |
| 1998 Jun 18     | 12.96 | 13.36 | 13.05 |
|                 | (0.04) | (0.04) | (0.04) |
| 1998 Jun 19     | 12.86 | 13.28 | 12.92 |
|                 | (0.02) | (0.04) | (0.04) |

## Table 3

| Date            | $P_r$  | P.A.  |
|-----------------|--------|-------|
| 1998 Jun 17     | 0.16 ± 0.16 | -3.19 ± 5.22 |
| 1998 Jun 18     | 0.22 ± 0.30 | 1.80 ± 9.18 |
| 1998 Jun 19     | 0.25 ± 0.14 | 1.19 ± 4.35 |
| 1998 Jun 20     | 0.29 ± 0.13 | -3.00 ± 3.70 |
| 1998 Jun 21     | 0.15 ± 0.18 | -4.33 ± 5.54 |
| 1998 Jun 22     | 0.42 ± 0.20 | -4.08 ± 5.59 |
| 1998 Aug 26     | 0.20 ± 0.17 | -1.72 ± 4.88 |
| 1998 Aug 27     | 0.17 ± 0.13 | -4.83 ± 3.75 |
| 1998 Aug 28     | 0.18 ± 0.10 | -5.03 ± 2.83 |
| 1999 Aug 1      | 0.01 ± 0.29 | -3.66 ± 8.19 |
| 1999 Aug 2      | 0.06 ± 0.11 | -1.21 ± 3.43 |
| 1999 Aug 3      | -0.05 ± 0.18 | 3.00 ± 5.32 |
| 1999 Aug 5      | 0.14 ± 0.24 | -2.80 ± 7.41 |
defined the parameters

$$P_v = \frac{d \log P}{d \log \nu},$$

and

$$\text{P.A.}_v = \frac{d \text{P.A.}}{d \log \nu},$$

which describe the spectral shape of the polarization percentage and position angle, and determined them by fitting power laws to the daily averages of the $UBVRI$ linear polarization percentages and position angles. Table 3 reports the values of $P_v$ and $\text{P.A.}_v$ with their standard deviations as resulting from the fit. While in some nights $P_v$ is obtained with more than 2 $\sigma$ confidence, the fitted $\text{P.A.}_v$ values are poorly determined. The suggestion is that the best determined ones (1998 August 27 and 28) are negative; namely, the P.A. increases toward the red wavelengths.

### 3.3. Circular Polarization

Results on circular polarization are reported in Table 1. Generally, no significant detection is present; marginally significant (slightly less than 3 $\sigma$) circular polarization is seen in $UBV$ bands on 1998 November 19 at a level consistent with $-0.2\%$ in all filters, within 1 $\sigma$.

No clear pattern is deduced from comparison of values in different filters in the other nights, nor is it discerned any preferred value, in a given filter, by comparison among different nights. Conservatively, we set an upper limit of 0.2% at the 3 $\sigma$ level for our measurement of circular polarization of PKS 2155–304.

### 3.4. Correlation between Polarimetry and Photometry

The CASLEO photometry agrees well with the Córdoba photometry, as seen in Figure 5. Variability between successive runs (on intervals of months) is always present and amounts to some tenths of a magnitude, with no apparent correlation with polarization. Variations within the same night and from night to night in the same run are observed at a level up to $\sim 10\%$, and will be discussed in E. Poretti et al. (2001, in preparation).

Generally, variations of the total and polarized flux are not found to be correlated within the same run. In particu-
lar, the sharp decrease of the linear polarization that occurred on 1998 June 18 had no counterpart in the CASLEO photometry (see Table 2), and the significant decrease of polarization between 1999 August 2 and August 3 corresponds to a practically unaltered photometric state, as shown by the CASLEO and Córdoba photometry in Table 2. Similarly, no correlation is found on intranight scales. In particular, during the night of 1998 August 28, no correlated variation in total flux has been recorded simultaneous with the strong variability of polarization percentage in the early portion of the run (see Fig. 2b). The smooth and broad maximum present in the total light curve in the central part of the night cannot be reliably correlated with the fast variation seen in our polarimetric data.

4. COMPARISON WITH PREVIOUS POLARIMETRIC RESULTS

As mentioned above, PKS 2155−304 has been the target of various optical polarimetric campaigns in previous years. We compared our results with those reported in the literature by representing in histograms $P$ and P.A. values from previous measurements and from our own (Fig. 6). Both distributions exhibit a broad peak, indicating some historical preferred values. The peak of polarization percentage occurs at about 5.5%. The distribution is strongly asymmetric, with an apparent tail toward values larger than 10%. P.A. values are mostly included in the interval 90°−160°, with a mode ~115°. However, many strongly deviating values were recorded, both in the past and in our observations. In particular all the P.A.'s lying between 50° and 80°, as well as one of those smaller than 10°, were observed during our campaigns.

5. DISCUSSION

We have obtained polarimetric data of PKS 2155−304 over long time intervals at a high sampling rate that is without precedent. This allowed us to study in detail the long- and short-term polarization variability of the source, in particular the intranight events, and the shape of the polarized spectrum.

Possible dilution of the polarization due to the host galaxy of PKS 2155−304, a giant elliptical, is expected to
be wavelength dependent because its spectrum should be significantly redder than that of the nucleus. In fact, given the measured magnitudes of the host galaxy \((M_r = -26.8; M_I = -24.2; M_H = -26.8; M_K = -18.2; M_J = -19.3; M_Z = -19.6)\) reported in Falomo et al. (1991), using the color indices of a typical elliptical galaxy reported by Fukugita, Shimasaku, & Ichikawa (1995), Kotilainen et al. (1998), and Bertone et al. (2000), we calculated the host galaxy flux \(F_{\text{host}}\) in the \(UBVRI\) bands. Given the diameter of the projected aperture size for photopolarimetry and the effective de Vaucouleurs radius for the host galaxy reported in Falomo et al. (1991) (4.5 in the Gunn I filter) and Kotilainen et al. (1998) (175 in the \(H\) band), we assume that 100% of the galaxy flux \(F_{\text{host}}\) is included in our photometry. Then, by subtracting it from the total light (AGN + galaxy) represented by the magnitudes in Table 2, we computed the AGN flux \(F_{\text{AGN}}\). Finally, using the hypothesis that the host galaxy only dilutes the polarization percentage of the AGN with its total flux contribution, and ignoring depolarization by Faraday rotation, we estimated the intrinsic polarization of the AGN light according to

\[
P_{\text{int}} = P_{\text{meas}} \left(1 + \frac{F_{\text{host}}}{F_{\text{AGN}}}\right),
\]

where \(P_{\text{meas}}\) are from Table 1. The result for the night of 1998 August 28, one of the nights with the best determined WDP, is a constant polarization \(P = 7.1\%\) over the \(UBVRI\) bands. Observed values of \(P\) smaller than that of 1998 August 28 have all larger errors (see Table 3), and therefore the corresponding corrected \(P\) indices are not significantly below zero (except the marginally significant case of 1999 August 3). Therefore, no strong evidence is present of negative WDP in our data. We note that our aperture also includes light from a galaxy located at 4” from the BL Lac nucleus (G1; Falomo, Pesce, & Treves 1993). However, its emission \((m_K \sim 20)\) does not contribute significantly to the depolarization. We also neglected any possible polarization induced by dust scattering in the host, this being usually several orders of magnitude smaller than the AGN synchrotron polarization.

Past studies (Smith & Sitko 1991) based on WDP have excluded that an accretion disk is contributing significantly to the optical emission of PKS 2155—304, in which case higher polarization would be expected at longer wavelengths. Similar conclusions were reached by Urry et al. (1993) based on the correlated behavior of the optical and UV light curves. Our finding of a flat polarized spectrum is consistent with the conclusions of Smith & Sitko (1991).

As proposed to explain optical polarization of GRB afterglows (Gruzinov & Waxman 1999; Medvedev & Loeb 1999), which exhibit polarization levels comparable to this and other blazars, one can envisage two scenarios: one with a highly ordered magnetic field, and one with a highly tangled field. The two cases can be distinguished basing on position angle measurements: a constant P.A. indicating the former case, a variable P.A., the latter. Our measurements of PKS 2155—304, combined with the historical ones, suggest the following scenario. A component endowed with a regular magnetic field, usually dominant, is responsible for the preferred P.A. \(\sim 115^\circ\). The event recorded on 1998 June 18, with a sudden decrease of \(P\) and rotation of the P.A., suggests, instead of a large and rapid rotation of the magnetic field axis, a quenching of the ordered component, and the emerging of a different component, with a more tangled field. The lower level of polarization in this case can be explained with the presence of \(n\) subregions, or “patches,” each with a size comparable to the coherence.
length of the magnetic field, so that the net $P$ is given by $P_{\text{max}}/\sqrt{n}$, where $P_{\text{max}}$ is the polarization of each individual patch (Gruzinov & Waxman 1999; Wijers et al. 1999). From the measurement of $P$ in low state ($\sim 1\%$) and from the expected polarization of the synchrotron radiation ($\sim 70\%$), one deduces a number of patches of $\sim 5000$. The ordered-field component could be associated with a jet observed slightly off-axis, as envisaged by Covino et al. (1999), Ghisellini & Lazzati (1999), and Medvedev & Loeb (1999).

However, also the rise of a single component with orthogonal polarization plane could explain the sudden decrease in $P$ accompanied by a 90° rotation of the P.A.

Smaller timescale (intranight) variations of $P$ can be interpreted with physical changes within the jet (modifications of the electron energy distribution law owing to a propagating shock or small variations in magnetic field strength), while short-term variations in P.A. can be due to geometric variations (varying orientation of jet or magnetic field vector). Note that a detailed model should account for the absence of correlation between the polarized and total flux that is shown in the observations reported here.

Previous reports of optical circular polarization measurements in blazars include marginal detections by Takalo & Sillanpää (1993) for 3C 66A and OJ 287 and by Valtaoja et al. (1993) for PKS 0735 + 178 and PKS 0422 + 004. For PKS 2155 – 304, only measurements with HST in the UV are reported (Allen et al. 1993). The absence of significant circular polarization, in a simple and homogeneous scenario, agrees with expectation that this should be a factor $\gamma_e$ less than the linear $P$, where $\gamma_e$ is the Lorentz factor of the electrons, and therefore out of reach of our accuracy, given that in blazars typically $\gamma_e > 10^4$. More complex scenarios, with inhomogeneous jets and helical magnetic fields (Valtaoja 1984), foresee larger relative values of circular polarization with respect to linear polarization. This could be invoked if the hint of circular polarization detection of $\sim 0.2\%$ on 1998 November 19 turned out to be real.

Since the polarized flux in PKS 2155 – 304 is produced by synchrotron radiation in the nuclear region, with very small dilution from the host galaxy, we expect $P$ variations to be well correlated with those of the X-ray flux (see also Smith et al. 1992). For the same reason, we do not expect radio polarization variations to be correlated with the optical polarization because the former originate in more extended regions, external to the inner nucleus. Simultaneous monitoring of PKS 2155 – 304 at optical to X-ray frequencies could help discerning the exact causes of small timescale variability and advance our understanding of the physical behavior of “blue,” synchrotron-dominated blazars.

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