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VRI photometry of stars in the fields of 12 BL Lacertae objects⋆

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Abstract. — We present VR_cI_c Johnson-Cousins magnitudes of field comparison stars for twelve BL Lacertae objects belonging to the largest sample of blazars which is monitored at the Perugia University Observatory. The sequences reported here can be used in the long–term CCD photometric monitoring of BL Lac objects aimed to understand the characteristics of their variability. Finding charts for all of these comparison sequences are also included in this paper.

Key words: BL Lacertae objects: general

1. Introduction

BL Lacertae objects (BL Lacs) are radio–loud active galactic nuclei (AGN), characterized by rapid and large amplitude variability, high and variable flux polarization, absence of emission or absorption lines in the spectra (Stein et al. 1976; Angel & Stockman 1980). Most of these objects show superluminal motion, and they are among the few extragalactic sources emitting high–energy gamma rays (Fichtel et al. 1994; von Montigny et al. 1995). BL Lacs are often grouped together with optically violent variable (OVV) quasars to form an AGN subclass called "blazars".

All the observational evidences mentioned above can be explained with the hypothesis that BL Lacs are an extreme variety of AGN with the relativistic jet aligned with our line of view (Blandford & Rees 1978). The study of the variability shown by this class of objects is then one of the most important tools to explore the physics of the central engine of AGN.

Since 1992 we are carrying out a monitoring program of about 40 blazars using an automatic 0.40 m telescope at the Perugia University Observatory. The telescope is equipped with a CCD camera and V R_c I_c Johnson–Cousins filters, which are extensively used for typical CCD photometry.

Up to date for many BL Lacs, comparison stars have been calibrated only in the UBV bands (see, e.g., Craine 1977; hereinafter C77, and references therein) and scarce are the sequences for the R_c and I_c filters. Recently Smith et al. (1985, hereinafter S85) and Smith et al. (1991, hereinafter SJE91), published $UBVR_cI_c$ magnitudes for comparison sequences of some BL Lacs. However many other objects, included in our sample, have not comparison stars in their fields.

Here we report VR_cI_c magnitudes and finding charts for comparison stars in the fields of twelve BL Lac objects. This is the first result of a larger work that we are devoting to calibrate VR_cI_c field comparison stars located within a few arcminutes from blazars which have been brighter than $V = 17$ at some time. We believe that this could be useful to extend the sample of blazars for which is possible to obtain differential photometry, with the aim to collect more information about this important class of AGN.

The paper is organized as follows. In Sect. 2 the observations and the data reduction are summarized. Section 3 contains the basic results and a detailed comparison with other published works that have at least one star in common with those stars we have calibrated.

2. Observations

Table 1 gives the list of BL Lacs in the fields of which we have observed the comparison stars. Column (1) reports the object name, Cols. (2) and (3) give the J2000 coordinates. The redshift, when known, is given in Col. (4). Other source designations commonly used in literature are listed in Col. (5).

In Table 1 we list BL Lacs without any known VR_cI_c comparison sequences; BL Lacs with comparison stars calibrated only in the V band (or in the U and B bands) but not in the R_c and I_c; BL Lacs with only one (or any) previously calibrated comparison star within the limits of our camera field of view (3C66A, MKN 501 and H1722+119) for which we added new stars to the existing sequences; BL Lacs with published comparison stars which photometric

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⋆Table 3 is only available in electronic form at the CDS via anonymous ftp 130.79.128.5

Table 1. List of BL Lac objects selected in this article

Name(1)	R.A.(2000)	Dec(2000)	z	Other names
3C 66A	02 22 39.6	43 02 08	0.444	4C 42.07, NRAO 102
PKS 0829+046	08 31 48.8	04 29 39	0.180	OJ 049
OJ 287	08 54 48.8	20 06 30	0.306	PKS 0851+203, B2 0852+20
B2 1147+24	11 50 19.1	24 17 53		OM 280
B2 1215+30	12 17 52.1	30 07 00		ON 325, PKS 1215+303
ON 231	12 21 31.6	28 13 57	0.102	W Com, B2 1219+28
PKS 1424+240	14 27 00.4	23 47 57		
MARK 501	16 53 52.1	39 45 36	0.033	OS 387, PKS 1652+398, 4C 39.49
H 1722+119	17 25 04.2	11 52 14		4U1722+11
I ZW 187	17 28 18.5	50 13 11	0.055	OT 546, PKS 1727+50
PKS 2032+107	20 35 22.3	10 56 06	0.601	OW 154.9
BL Lac	22 02 43.2	42 16 40	0.069	OY 401, PKS 2200+420

NOTES: (1) as reported by Véron–Cetty & Véron (1993).

data were not in accord with our measurements (OJ 287 and BL Lac).

All the observations were made using the 0.40 m newtonian reflector ($f/5$) at the Perugia Astronomical Observatory. This telescope was recently automatized to perform unattended CCD photometry (Tosti et al. 1996). We used a CCD camera based on the Texas Instrument chip TC211 having 192×165 pixels, that has a field of view of $5' \times 5'$ at the newtonian focus. It is cooled by Peltier stages that reduce the CCD temperature by almost 50°C with respect to the ambient temperature. This CCD has a good quantum efficiency, is cheap, not bulky, fully linear and, in particular, is very uniform (> 99%). Nevertheless it has high readout noise and dark signal; for this reason a dark frame, with the same exposure time, must be taken after each object image.

The CCD camera is equipped with V $R_{\rm c}$ $I_{\rm c}$ filters of Johnson-Cousins made joining Schott filter glasses in the following combinations:

$$V: \quad \mathrm{GG495\ (2\ mm)} + \mathrm{BG39\ (2\ mm)}$$

$$R_{\rm c}: \quad \mathrm{OG570\ (2\ mm)} + \mathrm{KG3\ (2\ mm)}$$

$$I_{\rm c}: \quad \mathrm{RG9\ (3\ mm)}$$

Taking into account the CCD spectral response, the photometric system matches well the standard system described by Bessell (1979).

The data utilized to calibrate the comparison stars for the objects listed in Table 1 were taken during a total of 35 photometric nights, from January 1994 to June 1995. The atmospheric extinction was determined each night using the standard stars given by Landolt (1983a, b). The exposure integration times, both for comparison and standard stars, varied from 2 to 10 min depending on the brightness of the objects. The CCD frames were corrected for bias and dark signal. Because of the high grade of uniformity of our CCD chip the usual flat field correction of the images was not required. Instrumental magnitudes were obtained in simulated 8 arcsec aperture radius photometry using DAOPHOT routines (Stetson 1987). Internal checks were done to eliminate possible imperfections (e.g. cosmic ray traces) and to evaluate the goodness of the mode and skew values in the annular sky region around each star.

The transformation equations utilized to obtain the standard values from instrumental magnitudes corrected by atmospheric extinction (denoted with the index "$\circ$") were:

$$V - v_\circ = \alpha_v + \beta_v (v - r)_\circ$$

$$R_{\rm c} - r_\circ = \alpha_r + \beta_r (v - r)_\circ$$

$$I_{\rm c} - i_\circ = \alpha_i + \beta_i (v - i)_\circ$$

The values of the coefficients in the preceding equations were estimated by performing least–squares linear regressions using the data obtained by observing in each photometric night a sample of standard stars (Landolt 1983a, b). Table 2 lists the mean transformation coefficients together with their standard errors and the typical standard deviations of the fit ($\sigma_{\rm f}$). From the data in Table 2 and taking into account the errors in the measurement of the instrumental magnitude of each star (normally 0.02 mag), we can conclude that our absolute photometry has a typical standard deviation of 0.05 mag, a value that is more than acceptable in many variability studies of blazars.

Table 2. Transformation coefficients to the standard system

	α	β	$\sigma_{\rm f}$
V - $v_\circ$	16.69 ± 0.03	-0.01 ± 0.01	0.04
$R_{\rm c}$ - $r_\circ$	16.72 ± 0.03	0.00 ± 0.01	0.04
$I_{\rm c}$ - $i_\circ$	16.14 ± 0.03	0.02 ± 0.02	0.04

3. Results

For each BL Lac object listed in Table 1, at least two comparison stars were chosen among the closest bright

stars. When comparison stars were already reported in the literature for at least one filter (in general only UBV data were available), we made VR_cI_c calibration only for those stars well observable with our telescope and, when possible, other bright stars were added to the sequence.

Finding charts (Fig. 1) for the comparison stars around the twelve BL Lacs were extracted from the STScI Digitized Sky Survey (DSS) accessible via World Wide Web.

Table 3 (available electronically) summarizes our photometric results. The names of the comparison stars are given in Col. (1), below the name of the BL Lac object to which they are referred. We used the letter "C" followed by a progressive number to label the comparison stars that were calibrated, as far as we know, for the first time in this work. Columns (2) and (3) give the coordinates of the stars measured directly on the DSS. The VR_cI_c magnitudes and the associated errors are given in Cols. (4)-(6). For most of the fields reported in this work we have many observations obtained in different photometric nights, but in Col. (7) of Table 3 we report only the number of nights in which we obtained the better CCD images and the data with the higher signal to noise ratio. The magnitudes with the associated standard deviations, reported in the table are weighted means of the values obtained in such nights. We also checked the variability of these stars analysing the differences in magnitudes during our monitoring program (Fiorucci & Tosti 1996), and we accepted as comparisons only the stars with no indication of variability during the monitoring campaign (fluctuations less than 3 times the standard deviation).

Column (8) of Table 3 gives the references for those objects that have previously published photometric sequences in at least one of the VR_cI_c filters. In these cases the designations used in Col. (1) for the common stars are the same reported by references.

For the object 3C 66A, C77 reported V magnitudes for the stars A and B (V=13.56 for star A and V=14.77 for star B) while Takalo et al. (1994, hereinafter TSN94) measured the star A in all the filters (V=13.57±0.02, R_c=13.36±0.03, I_c=13.01± 0.03). Both calibrations are in good agreement with the data reported in this article.

OJ 287 is one of the most observed BL Lac objects, but there is not a good agreement among the previously published data for the comparison stars 4, 10 and 11 (see Table 4). The V magnitude of star 4 in S85 is brighter than the values obtained by the observations of Penston & Wing (1973) by 0.1 mag. For the same star our observations give an intermediate V magnitude, with the color indices $V - R_c$ and $V - I_c$ in good agreement with the values given by S85. Considering the standard deviations there is, in the V band, a reasonable agreement for star 10 among the data of Penston & Wing (1973), S85, TSN94 and our work. Nevertheless our data allow a better estimate for R_c ad I_c mean values, confirming a difference of almost 0.1 mag with respect to S85, difference already noted by Heidt et al. (1994) and in agreement with TSN94. Table 4 also shows a good agreement in the magnitudes of star 11. Besides, we have added two new comparison stars in the field of OJ 287 (see the finding chart in Fig. 1) useful in the cases of decentered images.

For the B star in the field of B2 1215+30 there is good agreement with the V magnitude reported by C77 (V=14.95). The same is valid for stars A and D in the field of ON 231 (C77 reports V=12.08 for star A and V=14.82 for star D) and for star B, L and H near I ZW 187 (C77 reports V=13.11 for star B, V=15.33 for star H and V=16.14 for star L). No previously published data are available in R_c and I_c bands for these objects.

Star A in the field of MKN 501 was calibrated in the $UBVR_cI_c$ bands by SJE91 (V=12.61±0.01, R_c=12.11±0.01 and I_c=11.63±0.01). This star was calibrated in the UBV bands by Véron & Véron (1976) (V=12.65) and reported with the name of "star 3". With respect to both these papers there is a good agreement with the observations reported in this work. For MKN 501 we have calibrated two new stars near the BL Lac object because the star B given by SJE91 was always outside the field in our images. The calibration of these stars can be very useful for better estimates in differential photometry.

Also H1722+119 has $UBVR_cI_c$ sequences calibrated by SJE91, but too far from the BL Lac object to be useful with a CCD camera having a small field of view, so we have measured the VR_cI_c magnitudes of four new comparison stars.

BL Lac, the prototype for this class of AGN, has a systematic discrepancy in the previously published V data for the stars B, C, H, K. Table 5 gives the magnitudes of these stars as reported in the V band by Bertaud et al. (1969) and the VR_cI_c magnitudes observed by S85. Bertaud et al. (1969) did not report explicitly the standard deviations of their observations, giving only an estimated error value less than 0.1 mag for the stars H and K, while they assured a high level of precision for the photometric measurements of stars B and C. Our V observations agree very well with the data of Bertaud et al. (1969), but are almost 0.1 mag fainter than the magnitudes obtained by S85. The data of S85 appear to be bright of almost 0.1 mag also in the U and B bands, compared to the data of Bertaud et al. (1969) and, in the R_c and I_c bands, as regards to this work. This could be a systematic effect.

For the other BL Lac objects (PKS 0829+046, B2 1147+24, PKS 1424+240 and PKS 2032+107), as far as we know, no reference stars near a few arcmins were previously published, so our contribution can be very useful for a more systematic study of optical variability and spectral changes for these objects.

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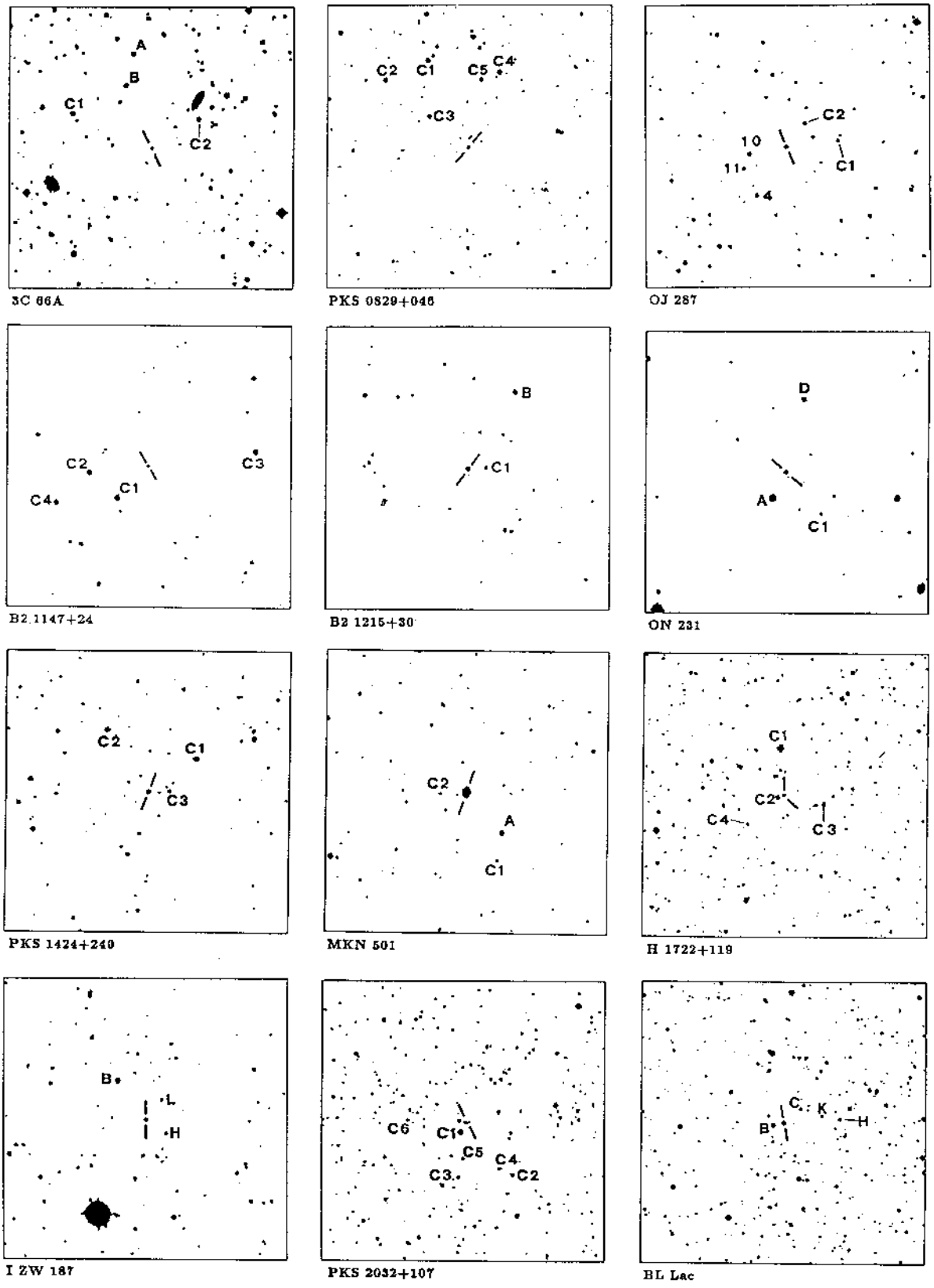

Fig. 1. Finding charts of the field comparison stars reported in this article. All charts are obtained from the STScI Digitized Sky Survey. North is at the top and east is to the left. Each squared box is 10′ wide and it is centered to the BL Lac object

Table 4. Comparison with previous calibrations in the field of OJ 287

Star	filter	PW73[1]	S85[2]	TSN94[3]	this work
4	V	14.24 ± 0.01	14.14 ± 0.05		14.18 ± 0.04
4	R_c		13.72 ± 0.06		13.74 ± 0.04
4	I_c		13.23 ± 0.07		13.28 ± 0.04
10	V	14.56 ± 0.05	14.56 ± 0.04	14.53 ± 0.02	14.60 ± 0.05
10	R_c		14.26 ± 0.06	14.35 ± 0.05	14.34 ± 0.05
10	I_c		13.94 ± 0.09	14.05 ± 0.03	14.03 ± 0.05
11	V	14.94 ± 0.05	14.96 ± 0.05		14.94 ± 0.04
11	R_c		14.67 ± 0.07		14.65 ± 0.05
11	I_c		14.29 ± 0.09		14.32 ± 0.05

NOTES: (1) Penston & Wing (1973), (2) Smith et al. (1985), (3) Takalo et al. (1994).

Table 5. Comparison with previous calibrations in the field of BL Lac

Star	filter	B69[1]	S85[2]	this work
B	V	12.90	12.78 ± 0.04	12.90 ± 0.04
B	R_c		11.93 ± 0.05	11.99 ± 0.04
B	I_c		11.09 ± 0.06	11.12 ± 0.05
C	V	14.28	14.19 ± 0.03	14.26 ± 0.06
C	R_c		13.69 ± 0.03	13.79 ± 0.05
C	I_c		13.23 ± 0.04	13.32 ± 0.05
H	V	14.42 (<0.10)	14.31 ± 0.05	14.40 ± 0.06
H	R_c		13.60 ± 0.03	13.73 ± 0.06
H	I_c		12.93 ± 0.04	13.07 ± 0.06
K	V	15.48 (<0.10)	15.44 ± 0.03	15.47 ± 0.07
K	R_c		14.88 ± 0.05	15.00 ± 0.06
K	I_c		14.34 ± 0.10	14.54 ± 0.07

NOTES: (1) Bertaud et al. (1969), (2) Smith et al. (1985).

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