

# Extremely violent optical microvariability in blazars: fact or fiction?\*

Sergio A. Cellone,<sup>1†</sup> Gustavo E. Romero<sup>1,2</sup> and Anabella T. Araudo<sup>1,2</sup>

<sup>1</sup>*Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque, B1900FWA La Plata, Argentina*

<sup>2</sup>*Inst. Argentino de Radioastronomía, C.C.5, 1894 Villa Elisa, Buenos Aires, Argentina*

Accepted 2006 October 3. Received 2006 October 2; in original form 2006 September 7

## ABSTRACT

Variability amplitudes larger than 1 mag over time-scales of a few tens of minutes have recently been reported in the optical light curves of several blazars. In order to independently verify the real occurrence of such extremely violent events, we undertook an observational study of a selected sample of three blazars: PKS 0048–097, PKS 0754+100 and PKS 1510–089. Possible systematic error sources during data acquisition and reduction were carefully evaluated. We indeed found flux variability at intra-night time-scales in all the three sources, although no extremely violent behaviour, as reported by other authors, was detected. We show that an incorrect choice of the stars used for differential photometry will, under fairly normal conditions, lead to spurious variability with large amplitudes on short time-scales. Wrong results of this kind can be avoided with the use of simple error-control techniques.

**Key words:** galaxies: active – BL Lacertae objects: general – galaxies: photometry.

## 1 INTRODUCTION

One distinctive characteristic of active galactic nuclei (AGN) is the fact that their energy flux varies along the whole electromagnetic spectrum, spanning a wide range of time-scales. Indeed, flux variability is an often-used criterion for AGN detection (e.g. Mushotzky 2004). Within the widely accepted canonical model, i.e. super-massive black hole (SMBH) + accretion-disk (AD) + dusty torus (DT) + relativistic jets, different regions of the active nucleus are thought to contribute to the power emitted at different frequencies along the spectral energy distribution (SED). On the other hand, variability time-scales strongly constrain the sizes of the emitting regions through light-travel arguments. Since, except for the Mpc-scale radio-jets and lobes, the other components remain spatially unresolved to astronomical observations in the vast majority of AGNs, flux variability studies are thus a powerful tool to probe those innermost regions.

While most AGNs are variable on time-scales of a few years, blazars, i.e. the subclass comprising BL Lac objects and flat-spectrum radio-quasars (FSRQ), display both the largest amplitudes and shorter time-scales. At optical wavelengths, long-term variations, with amplitudes of  $\sim 2$  to  $\sim 5$  mag along a few years, have been found through extensive monitoring in several objects, such as GC 0109+224 (Ciprini et al. 2003), AO 0235+164 (Raiteri et al. 2005) and OJ 287 (Qian & Tao 2003). Optical fluctuations on time-

scales spanning several days are also usually observed, although with smaller amplitudes (e.g.  $\sim 1$  mag in 20 d for PKS 2005–489, Dominici et al. 2004;  $\sim 1.7$  mag in 10 d for 3C 454.3, Fuhrmann et al. 2006).

Although photometric changes for blazars on very short time-scales were reported more than 30 yr ago ( $\Delta m \simeq 0.3$  mag in less than 24 h for BL Lac, Racine 1970), this phenomenon remained unrecognized by most astronomers until the advent of CCD detectors, when the existence of the now called intra-night optical variability (INOV) or *microvariability* was firmly established (Miller, Carini & Goodrich 1989; Carini, Miller & Goodrich 1990; Carini et al. 1991, 1992). Soon it became clear that several sources could experience remarkably large intra-night fluctuations, amounting to several tenths of a magnitude in a few hours. This is the case, among others, for PKS 0537–441 (Tanzi et al. 1986; Heidt & Wagner 1996; Romero, Cellone & Combi 2000b), 3C 371 (Carini, Noble & Miller 1998) and AO 0235+164 (Heidt & Wagner 1996; Noble & Miller 1996; Rabbette et al. 1996). For this last object, Romero, Cellone & Combi (2000a) found changes up to 0.5 mag within one night and  $\sim 1.2$  mag between consecutive nights, through well-sampled *V*- and *R*-band light curves. This was one of the most violent variability events ever observed at optical wavelengths in any blazar. The statistical incidence of microvariability in different classes of AGNs has been studied by several authors (Romero, Cellone & Combi 1999; Gopal-Krishna et al. 2003; Sagar et al. 2004; Stalin et al. 2005).

The observed optical flux in blazars originates in a part of the AD and the inner (pc-scale) portions of the jets. Disregarding gravitational micro-lensing effects, which probably apply to a small subset of particular sources (e.g. Nilsson et al. 1996), three broad classes of intrinsic models may explain optical microvariability: (i) hotspot models, involving instabilities in the AD (Mangalam &

\*Based on observations collected at the Complejo Astronómico El Leoncito, operated under agreement among CONICET, UNLP, UNC, and UNSJ, Argentina.

†E-mail: scellone@fcaglp.unlp.edu.ar

Wiita 1993), (ii) shock-in-jet models, based on a relativistic shock-front interacting with inhomogeneities or bends in the jet (Marscher & Gear 1985; Romero 1995; Romero, Combi & Vucetich 1995) and (iii) geometrical models where the jet changes its orientation relative to the observer, thus changing its Doppler factor (Gopal-Krishna & Wiita 1992; Marscher 1992). Violent phenomena, as those reported above, probably rule out models based on AD instabilities, needing, instead, relativistic beaming with high Doppler factors.

In recent years, several papers claimed the repeated detection of extremely violent variability events in some blazars, with amplitudes  $\Delta m \gtrsim 1$  mag in a few tens of minutes (Bai et al. 1998; Xie et al. 1999, 2001, 2002a,b, 2004; Dai et al. 2001). For example, these authors reported a 2-mag variation in  $\sim 40$  min for the highly polarized quasar (HPQ) PKS 1510–089; they also showed several sudden ( $\Delta t \lesssim 15$  min) ‘dips’ of  $\sim 0.9$  mag in the light curve of the EGRET blazar OJ 248 (0827+243). If confirmed, these extremely violent phenomena would require a complete reassessment of the mechanisms which are thought to be responsible of the energy generation in AGNs. As an illustration, let us mention that optical variability time-scales of a few tens of minutes would imply emitting regions smaller than the Schwarzschild radius for certain objects.

In contradiction to Xie et al.’s claims, Romero et al. (2002) found no such extremely violent variability events in a sample of 20 EGRET blazars observed with  $\sim 20$  min time resolution along two or more nights each, showing that the discrepancies between both works probably had their origin in different methods for error control. In particular, Romero et al. (2002) suggested that an inappropriate choice of the comparison and control stars used for differential photometry could result in spurious fluctuations in the differential light curve.

Since it is desirable to firmly establish which is the real minimum time-scale of blazar microvariability, we have undertaken an intensive monitoring campaign focused on three particular objects with previous claims of extremely violent flux variations in order to check this behaviour independently. We have made a careful analysis of the error sources involved in the differential photometry following well-established procedures, thus producing light curves in which the significance of any variation is quantitatively evaluated. This procedure allowed us to set on solid bases the microvariability behaviour of blazars, showing that most claimed extremely violent events, if not all, are very likely to be spurious results produced by an inappropriate error handling. In Section 2, we give details on the selected objects and the observations, while in Section 3 we describe our methodology, with special attention to the statistical error analysis. We show our results in Section 4. Spurious variability results are exemplified in Section 5. We close in Section 6 with some recommendations to future observers.

## 2 SAMPLE AND OBSERVATIONS

In order to independently check the reported events of extremely violent microvariability in blazars, we have selected three of the most variable objects according to Xie et al.’s papers (Xie et al. 1999, 2001, 2002a,b, 2004; Dai et al. 2001). Their names, equatorial coordinates, redshifts, catalogued visual magnitudes and classification are listed in Columns 1–6 of Table 1, respectively. Here follows a short description of each blazar.

**PKS 0048–097.** The optical spectrum of this BL Lac shows very faint emission lines, making its redshift determination rather uncertain (Rector & Stocke 2001). A historical ( $\sim 30$  yr) *B*-band light

**Table 1.** Selected objects.

Name	$\alpha_{2000.0}$ (h min s)	$\delta_{2000.0}$ ( $^{\circ}$ ' ")	$z$	$m_V$ (mag)	Type
PKS 0048–097	00 50 41.3	–09 29 05	0.22	17.4	BL Lac
PKS 0754+100	07 57 06.6	+09 56 35	0.27	14.5	BL Lac
PKS 1510–089	15 12 50.3	–09 06 00	0.36	16.5	HPQ

curve shows a 1.8-mag variation; in the visual band, flux changes up to  $\Delta V \simeq 2.7$  mag have been recorded. A larger variation is reported at infrared wavelengths, amounting to  $\sim 6$  mag (Fan & Lin 1999). On time-scales of several months, Falomo et al. (1993) reported a  $\Delta V \simeq 0.9$  mag variation.

Xie et al. (2002b) reported variations up to  $\Delta R = 0.32$  mag in 30 min (2001 January).

**PKS 0754+100.** This is another BL Lac whose redshift is still uncertain (Falomo & Ulrich 2000). Baumert (1980) reported variations up to  $\sim 2$  mag in its optical flux over long time-scales. This object also displayed fast polarization variability, both at optical ( $P_{\text{opt}} = 4\text{--}26$  per cent) and at infrared (IR) ( $P_{\text{IR}} = 4\text{--}19$  per cent) wavelengths (Puschell & Stein 1980). A *V*-band light curve compiled by Fan & Lin (2000) shows a  $\sim 3$  mag change in 10 yr, with smaller variations up to  $\Delta V \simeq 1$  mag in about 1 yr.

Bai et al. (1998) reported  $\Delta B = 0.47$  mag in 22 min, while Xie et al. (2004) claimed  $\Delta B = 0.56$  mag and  $\Delta R = 0.66$  mag in about 80 min.

**PKS 1510–089.** This is a well-studied FSRQ, with a hard X-ray spectrum (Singh, Shrader & George 1997) and a powerful gamma-ray emission, detected by EGRET (Thompson et al. 1993; Sreekumar et al. 1996). At radio frequencies, it has shown fast, large amplitude flux changes (Aller, Aller & Hodge 1981; Aller, Aller & Hughes 1996). Significant optical variations were first reported by Lü (1972) over a  $\sim 5$  yr time-scale. Its historical light curve since 1899 was reconstructed by Liller & Liller (1975), it shows a long-term variation with a maximum range  $\Delta B = 5.4$  mag, including an outburst in 1948, after which the source brightness faded by 2.2 mag in 9 d. Ghosh et al. (2000) report ‘irregular variability of this blazar on time-scales of days to weeks’, with a  $\Delta R \simeq 0.5$  mag brightening in 84 d.

Extremely violent events, with the highest amplitudes and shortest time-scales, were repeatedly claimed for this object:  $\Delta R = 0.65$  mag in 13 min (Xie et al. 2001),  $\Delta R = 2.0$  mag in 42 min (Dai et al. 2001) and  $\Delta V = 1.68$  mag in 60 min (Xie et al. 2002a). A  $\Delta R = 1.35$  mag ‘dip’ lasting  $\Delta t = 89$  min was reported by Xie et al. (2004) in the light curve of this blazar.

These three objects were the targets of our monitoring campaign, using the 2.15 m ‘Jorge Sahade’ telescope at CASLEO, Argentina, equipped with a Roper–EEV 1340  $\times$  1300 pixel CCD (gain: 2.3 electrons  $\text{adu}^{-1}$ ; read-out noise: 7.6 electrons). A focal-reducer provided a  $\sim 9$  arcmin diameter field, with a scale of 0.67 arcsec  $\text{pixel}^{-1}$ . The blazars PKS 0048–097 and PKS 1510–089 were followed during six consecutive nights in 2004 August, while PKS 0754+100 was observed along five nights (with a one-night gap, due to bad weather) in 2005 January. Atmospheric conditions were photometric for  $\sim 54$  per cent of our observations, with some cirrus and/or bad seeing during the remaining time. Moon illumination was always below 38 per cent during the 2004 August run and below 69 per cent during the 2005 January run.

Each object was repeatedly observed alternating between an  $R$  (Cousins) and a  $V$  (Johnson) filter. Integration times ranged from 150 to 300 s; thus, between 6 and 20 images of the same object and with the same filter were obtained each night.

Science frames were bias-corrected and then flat-fielded using master bias and flat-field frames (one flat for each filter) obtained by averaging 25 individual frames. The IRAF<sup>1</sup> package CCDRED was used for this purpose.

### 3 DATA ANALYSIS

#### 3.1 Statistical error analysis

The usual technique to obtain light curves for AGNs (and many other astronomical objects) is differential photometry, i.e. the magnitude of the target is measured against that of a comparison star recorded on the same CCD frame. In this way, small fluctuations due to non-photometric conditions are cancelled, since all star-like objects on the field of view are equally affected (Howell & Jacoby 1986). A second star, measured against the same comparison star, is often used as a stability check. In this way, variability is evaluated by comparing the dispersions of two light curves: target–comparison star ( $\sigma_T$ ) on the one hand, and control star–comparison star ( $\sigma$ ) on the other hand. Assuming that the second light curve should only be affected by instrumental variations (i.e. both stars are non-variable), a statistical criterion is often used (e.g. Jang & Miller 1997; Romero et al. 1999) by introducing a parameter  $C = \sigma_T/\sigma$  and requiring  $C \geq 2.576$  for the source to be considered as variable at a 99 per cent confidence level.

This technique is conceptually so simple that possible problems arising from its misuse are sometimes looked-over, thus leading to the feeling that differential photometry is almost immune to any error source. To prevent this, several works have made useful recommendations to observers, based on firm statistical bases. For example, Howell (1989) showed that very small (optimum) apertures maximize signal-to-noise ratio (S/N) for point-source observations, when used along with CCD growth curves to obtain instrumental magnitudes. However, it was later shown that such small photometric apertures should not be used for the particular case of an AGN embedded in a bright host galaxy, since this can lead to spurious variability results when the seeing full width at half-maximum (FWHM) changes along the observations (Cellone, Romero & Combi 2000).

Regarding the correct choice of stars for comparison and control, a key work is that by Howell, Warnock & Mitchell (1988, hereafter HWM88). These authors show that it is not sufficient to simply select non-variable field stars for that purpose; these stars should also closely match the target’s magnitude (colour matching is shown not to be so important). If not, the measured dispersion of the target–comparison light curve ( $\sigma_T$ ) will be different from that of the control–comparison light curve ( $\sigma$ ), just from photon statistics and other random-noise terms (sky, read-out noise), even in the absence of any intrinsic variations in the target.

Since suitable stars are not always found (especially for high-Galactic latitude fields), HWM88 give detailed calculations to derive a corrective factor  $\Gamma$  which properly scales  $\sigma$  in order to match the expected *instrumental* dispersion  $\sigma_{T(INST)}$  of the target–comparison light curve. The computation of  $\Gamma$  thus requires the knowledge of

the relevant CCD parameters, as well as mean values of the sky brightness and magnitudes of target and stars. Following HWM88 (their equation 13), this corrective factor can be written as

$$\Gamma^2 = \left( \frac{N_{S2}}{N_T} \right)^2 \left[ \frac{N_{S1}^2(N_T + P) + N_T^2(N_{S1} + P)}{N_{S2}^2(N_T + P) + N_T^2(N_{S2} + P)} \right], \quad (1)$$

where  $N$  stands for total (sky-subtracted) counts within the aperture, while subindices T, S1 and S2 correspond to the target, comparison star and control star, respectively. The factor  $P$  takes into account common noise-terms, being  $P = n_{\text{pix}}(N_{\text{sky}} + N_{\text{RON}}^2)$ , where  $n_{\text{pix}}$  is the number of pixels within the aperture,  $N_{\text{sky}}$  is the sky level and  $N_{\text{RON}}$  is the read-out noise. Median values are used for objects and sky.

Thus, using the scaled  $\sigma$ , the confidence parameter is now rewritten as the quotient between the observed target–comparison light-curve dispersion and its expected dispersion just from instrumental and photometric errors:

$$\frac{C}{\Gamma} = \frac{\sigma_T}{\Gamma \sigma} = \frac{\sigma_T}{\sigma_{T(INST)}}. \quad (2)$$

In the ideal case when all three objects are of the same magnitude, then  $\Gamma = 1$ , and the original definition of  $C$  is recovered.

Many AGN variability studies, although not explicitly applying HWM88’s method, use comparison and control stars with apparent magnitudes very close to that of the target object (e.g. Romero et al. 1999; Sagar et al. 2004), thus ensuring  $\Gamma \simeq 1$ . Their results are in this way trustworthy, since the variability confidence levels of all light curves are properly estimated. However, it is a fact that, whenever extremely violent variations have been claimed, they resulted from differential photometry using comparison and control stars more than  $\sim 2$  mag (and up to  $\sim 5$  mag) brighter than the AGN, and without any dispersion scaling. This flawed procedure leads to a severe overestimation of the confidence parameter. In what follows, we will further illustrate this point with results from our own observations.

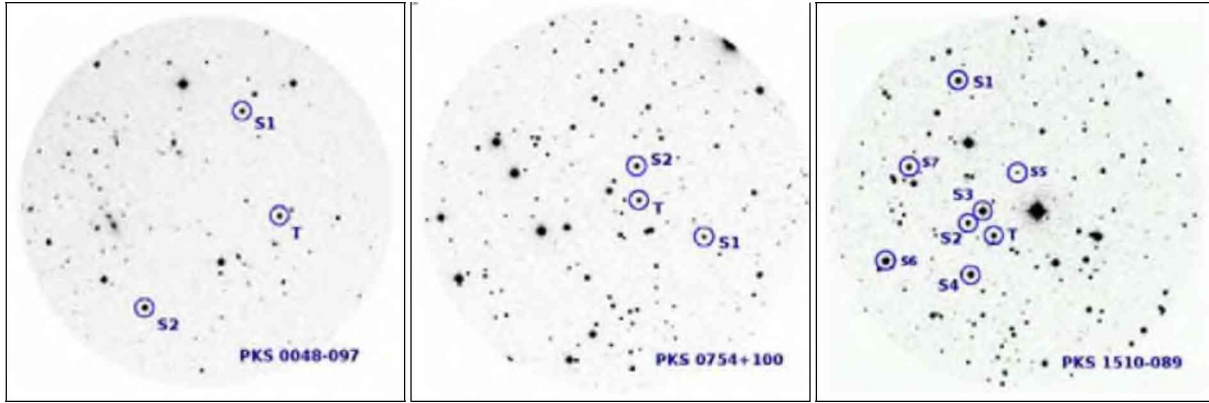
#### 3.2 Photometry

We used the IRAF package APPHOT to obtain aperture photometry for the three blazars and several isolated, non-saturated stars in each field. Aperture radii were set at 8 pixels (5.4 arcsec, i.e. between  $\sim 1.5$  and 2 times the seeing FWHM) in order to prevent against any unwanted effect due to light from the host galaxy under varying seeing conditions (Cellone et al. 2000). We then selected the two most suitable stars in each field to be used as comparison (S1) and control (S2), by requiring them to be non-variable and with magnitudes as close as possible to that of the blazar. In fact, the best results are obtained when S1 is slightly brighter than the target (HWM88), so, we tried to fulfil this condition, too.

We show finding charts for the three fields in Fig. 1. Note that we generally did not use known *standard* stars in the blazars’ fields, since most of these are too bright. The exceptions are star S2 in the field of PKS 0048–097, which is star no. 4 in Villata et al. (1998), and star S2 in the field of PKS 0754+100, which is star *D* in Miller, Mullikin & McGimsey (1983).

After constructing the differential light curves, they were checked for any suspicious data-points, such as sudden changes in the control light curve, and/or in only one of the photometric bands. A few of these events, due to cosmic-ray hits, were found and corrected. In the next section, we discuss our results.

<sup>1</sup>IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.



**Figure 1.** Finding charts for the observed fields. Each one is  $\sim 9$  arcmin across, with north up and east to the left-hand side. Our target blazars are marked with  $T$ , while  $S_i$  are the stars used for differential photometry (see text).

**Table 2.** Inter-night results.

Object	Filter	UT Date (yy/mm/dd–dd)	$\sigma$ [mag]	$\Delta t$ [h]	$C/\Gamma$	Variable?	$\Delta m_{\text{max}}$ [mag]	N
PKS 0048–097	$R$	04/08/08–13	0.007	122.50	13.61	Yes	0.31	53
	$V$		0.007	122.50	13.07	Yes	0.29	54
PKS 0754+100	$R$	05/01/14–19	0.008	125.21	10.18	Yes	0.36	74
	$V$		0.007	124.94	12.97	Yes	0.42	74
PKS 1510–089	$R$	04/08/08–13	0.006	122.24	31.89	Yes	0.61	55
	$V$		0.007	122.28	23.99	Yes	0.57	58

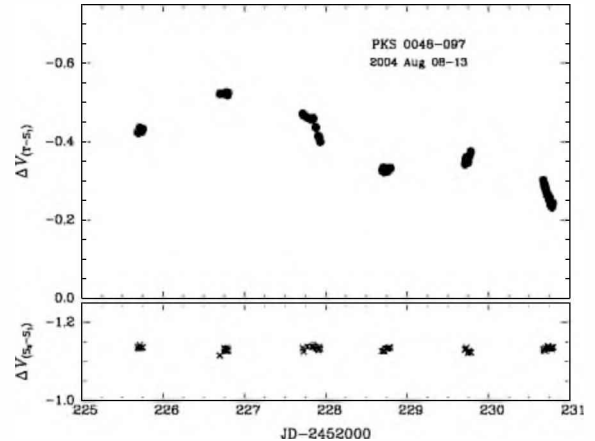
## 4 RESULTS

### 4.1 Inter-night results

Results from the whole campaign are given in Table 2, where Columns 1–6 are, respectively, object name, filter, dates of observation, control–comparison light-curve dispersion ( $\sigma$ ), total time between the first and last data points ( $\Delta t$ ) and scaled confidence parameter ( $C/\Gamma$ ). In Column 7, we state whether the blazar was variable or not during our observations, according to the adopted criterion. The last two columns give, respectively, the maximum variation amplitude (in magnitudes) along the whole campaign, and the total number of data points in each light curve. All light curves are graphically shown in Figs 2–4. Each figure shows the target–comparison light curve in the upper panel, and the control–comparison light curve in the lower panel against heliocentric Julian Date. Note that the vertical axis scale is always the same, in both panels of all the three figures.

It is evident that the three blazars were variable, with very high statistical significances, at these inter-night time-scales. Maximum amplitudes reached about half a magnitude for PKS 1510–089, and somewhat smaller values for the other two objects. Note that there is a good agreement between variability parameters in the  $V$  and  $R$  bands.

Individual error bars and control–comparison dispersions are larger for a few nights, when scattered moonlight and/or tracking errors affected our photometry. However, this had no evident impact on our ability to assess the object’s variability. On the other hand, the data corresponding to the fifth observing night for PKS 1510–089 are affected by a 0.065 mag zero-point shift due to technical problems. We corrected the graph in Fig. 4 for this effect, but we did not consider those data for the inter-night analysis.



**Figure 2.** Differential  $V$ -band light curve for PKS 0048–097, whole campaign. Upper panel: AGN– $S_1$ ; lower panel:  $S_2$ – $S_1$ .

### 4.2 Intra-night results

Tables 3–5 summarize the intra-night variability results for our three targets. Columns 1–6 give date of observation, filter, control–comparison light curve dispersion ( $\sigma$ ), time spanned by the observations ( $\Delta t$ ) and scaled confidence parameter ( $C/\Gamma$ ), respectively. Column 5 states whether the blazar was considered to be variable or not during each night. The last column gives the number of data points. We also show, for each blazar, the  $V$  light curve for the night when the largest variation was detected (Figs 5–7).

All three blazars displayed microvariability, with amplitudes up to  $\Delta m \simeq 0.08$  mag in 1 h; however, each of them was classified as

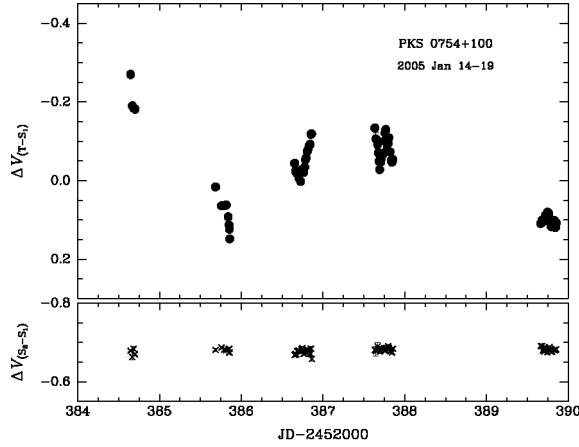


Figure 3. Same as Fig. 2 for PKS 0754+100.

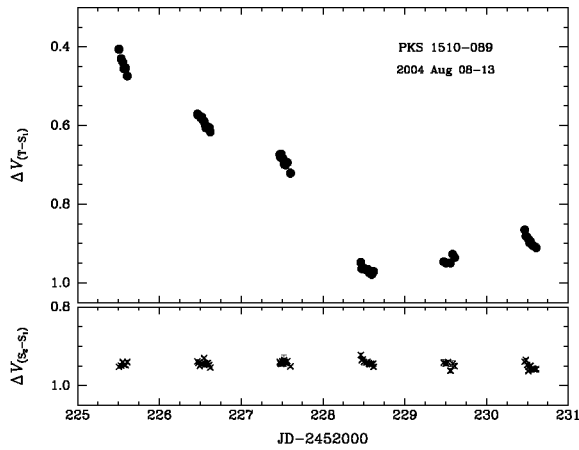


Figure 4. Same as Fig. 2 for PKS 1510-089.

Table 3. Intra-night results for PKS 0048-097.

UT Date (yy/mm/dd)	Filter	$\sigma$ [mag]	$\Delta t$ [h]	Variable?	$C/\Gamma$	N
04/08/08	R	0.004	1.44	No	1.35	6
	V	0.008	1.44	No	0.76	7
04/08/09	R	0.005	2.33	No	1.37	8
	V	0.007	2.38	No	0.27	8
04/08/10	R	0.008	5.11	Yes	3.22	10
	V	0.009	5.11	Yes	2.89	10
04/08/11	R	0.007	2.38	No	0.59	8
	V	0.005	2.38	No	0.80	9
04/08/12	R	0.006	1.66	No	2.56	9
	V	0.006	1.66	No	1.71	7
04/08/13	R	0.004	2.83	Yes	4.82	12
	V	0.004	2.78	Yes	5.54	13

non-variable for at least one night. This does not mean that, in such cases, the object's flux was completely constant; all we can say is that any possible variation was then below our confidence threshold.

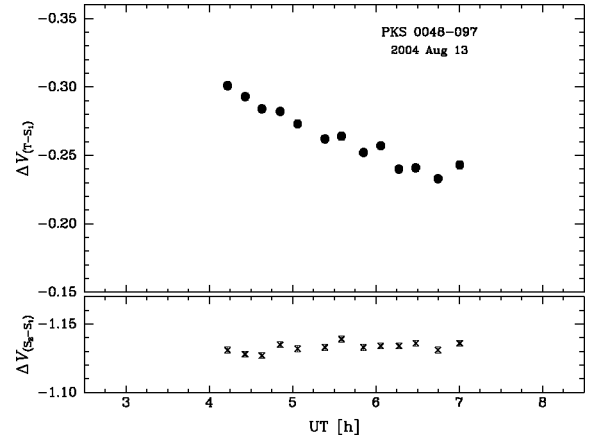
It is thus clear that no extremely violent behaviour was detected in any source along our whole campaign. The statistical significance of this result can be assessed as follows. Let us define the *duty cycle* (DC) for extremely violent microvariability as the fraction of

Table 4. Intra-night results for PKS 0754+100.

UT Date (yy/mm/dd)	Filter	$\sigma$ [mag]	$\Delta t$ [h]	Variable?	$C/\Gamma$	N
05/01/14	R	0.004	1.82	Yes	9.66	8
	V	0.011	1.27	Yes	4.02	8
05/01/15	R	0.007	3.91	Yes	5.78	10
	V	0.006	3.91	Yes	7.23	8
05/01/16	R	0.007	4.75	Yes	4.24	19
	V	0.008	5.02	Yes	4.58	20
05/01/17	R	0.010	5.33	Yes	3.01	20
	V	0.005	5.33	Yes	6.11	20
05/01/19	R	0.007	4.56	No	1.94	17
	V	0.006	4.51	No	1.81	18

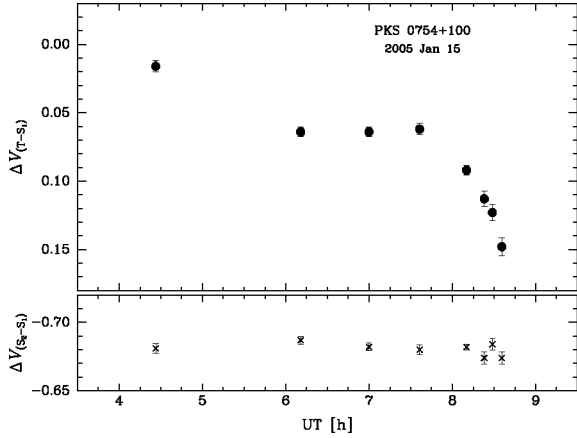
Table 5. Intra-night results for PKS 1510-089.

UT Date (yy/mm/dd)	Filter	$\sigma$ [mag]	$\Delta t$ [h]	Variable?	$C/\Gamma$	N
04/08/08	R	0.002	2.38	Yes	12.88	6
	V	0.004	2.45	Yes	6.68	6
04/08/09	R	0.004	3.74	Yes	3.38	12
	V	0.005	3.74	Yes	3.15	12
04/08/10	R	0.006	3.17	Yes	3.91	10
	V	0.004	3.17	Yes	3.75	10
04/08/11	R	0.004	2.38	No	2.16	11
	V	0.008	3.77	No	1.01	13
04/08/12	R	0.013	3.17	No	1.10	6
	V	0.008	3.24	No	1.16	6
04/08/13	R	0.005	3.38	No	2.42	10
	V	0.009	3.43	No	1.62	11

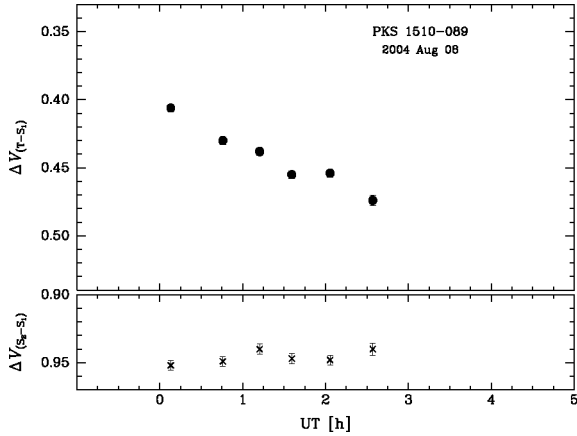

 Figure 5. Differential V-band light curve for PKS 0048-097, on the night of 2004 August 13. Upper panel: AGN-S<sub>1</sub>; lower panel: S<sub>2</sub>-S<sub>1</sub>.

the observing time for which the object displayed large amplitude ( $\Delta m \gtrsim 0.5$  mag), fast ( $\Delta t \lesssim 45$  min) flux changes. From the works by Xie's group (see Section 1), DC  $\simeq 50$  per cent is inferred; if we accept this number, the fact that we did not detect any such extremely violent event along 17 observing sessions would have a very low probability ( $\sim 10^{-5}$ ).

This result strongly implies that extremely violent microvariability reports should be carefully analysed, disentangling real flux changes in the source from systematic errors. In the next section,



**Figure 6.** Differential  $V$ -band light curve for PKS 0754+100, on the night of 2005 January 15. Upper panel: AGN– $S_1$ ; lower panel:  $S_2$ – $S_1$ .



**Figure 7.** Differential  $V$ -band light curve for PKS 1510–089, on the night of 2004 August 8. Upper panel: AGN– $S_1$ ; lower panel:  $S_2$ – $S_1$ .

we show how spurious results can be obtained from wrong error handling.

## 5 SPURIOUS VARIABILITY

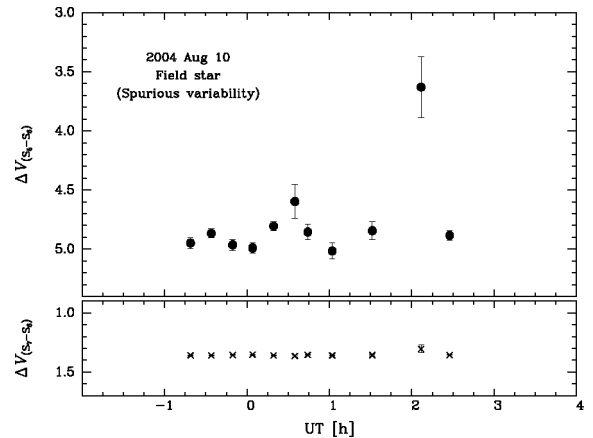
As an illustrative example of the effects of a bad choice of comparison and control stars, let us consider our data for PKS 1510–089 on the night of 2004 August 13. Our originally selected stars approximately follow the prescriptions given in Section 3.1:  $\Delta V(T - S_1) = 0.90$ ,  $\Delta V(S_2 - S_1) = 0.96$ ; i.e. comparison star not much brighter than target AGN and control star slightly fainter than the AGN. With these stars, we obtain a confidence parameter  $C = 1.55$ , and a scaled confidence parameter  $\frac{C}{T} = 1.62$ ; i.e. the blazar is classified non-variable in both cases. We now use two significantly brighter stars, shown as  $S_3$  and  $S_4$  in Fig. 1:  $\Delta V(T - S_3) = 1.95$ ,  $\Delta V(S_4 - S_3) = 0.58$  [ $S_3, S_4 \equiv$  star no. 4, star no. 6 in Raiteri et al. (1998)  $\equiv$  star A, star B in Villata et al. (1997), respectively]. This choice gives a confidence parameter  $C = 3.72$ , implying that the blazar should be considered as variable during that night. However, after correcting for the large flux difference between the objects, a scaled confidence parameter  $\frac{C}{T} = 1.32$  is obtained, thus classifying the target as non-variable.

The preceding analysis shows that, although a certain level of intrinsic variability may be present in the target, its significance is

severely overestimated when stars  $\sim 2$  mag brighter than the target are chosen for comparison and control. We now want to test if dramatic, although spurious, variability events may be produced when still brighter stars are used. Since any star more than  $\sim 3$  mag brighter than our targets was always saturated on our images, we selected a faint, non-variable star in the field of PKS 1510–089 to illustrate this effect. This star is labelled as  $S_5$  in Fig. 1, and we used stars  $S_6$  and  $S_7$  as comparison and control, respectively [ $S_6 \equiv$  star no. 5 in Raiteri et al. (1998)]. Hence, we reproduce a situation where the target is  $\sim 5$  mag fainter than the comparison star, while this last, in turn, is  $\sim 1.4$  mag brighter than the control star. The result of this completely inappropriate choice of stars is shown in Fig. 8: in about 1 h, the source seems to brighten by  $\sim 0.4$  mag, then returning to its original flux level; later, a spectacular ‘outburst’ brightens the object by  $\sim 1.2$  mag in about 35 min. Note the stability of the control–comparison light curve; without any dispersion scaling, the variability confidence parameter is  $C = 24.0$ , thus giving the impression of a highly significant flux variation. However, the scaled confidence parameter is just  $\frac{C}{T} = 1.0$ , clearly establishing that no significant variability is present in the data, with any fluctuation in the object – comparison light curve being the result of photometric errors differently affecting stars of very disparate magnitudes. In this particular case, both ‘outbursts’ coincide with sudden changes in atmospheric transparency, due to passing cirrus. Several factors contribute to make errors larger during such events: a lower flux level from the star, higher sky level and its associated rms, changes in the seeing FWHM, etc. Brighter stars are relatively less affected by these effects than the faint target, thus leading to the apparent variations in the differential light curve. Under different observational conditions and with different photometric techniques, it is likely that spurious ‘dips’ instead of ‘outbursts’ may be produced in the light curve.

These results underscore the absolute necessity of using the method described in HWM88 whenever suitable comparison and control stars cannot be found. Not doing so will very probably lead to spectacular, although completely false, results.

In some cases, extremely violent variability events have been claimed to be periodic (Xie et al. 2004). This is not surprising, since the observations are periodically repeated, and, if the same inadequate photometric techniques are used, similar spurious results



**Figure 8.** Differential  $V$ -band light curve for a faint non-variable star in the field of PKS 1510–089, on the night of 2004 August 10. Upper panel:  $S_5$ – $S_6$ ; lower panel:  $S_7$ – $S_6$ . The apparent extreme variability is just a spurious result.

will be obtained. These systematic errors have generated some completely ill-motivated theoretical models (Wu et al. 2005).

## 6 SUMMARY AND CONCLUSIONS

Repeated claims for the detection of extremely violent optical variability in blazars have been raised up in recent years (Xie et al. 1999, 2001, 2002a,b, 2004; Dai et al. 2001). These claimed events are characterized by fast flux changes  $\Delta m \gtrsim 0.5$  mag in a few tens of minutes, and reaching up to, for example, a 2-mag variation in  $\sim 40$  min reported for PKS 1510–089. However, other studies have found that the typical minimum time-scale for such large-amplitude variations in blazars is of several hours or still larger (e.g. Romero et al. 2002). We have thus undertaken an observational campaign, targeting the blazars PKS 0048–097, PKS 0754+100 and PKS 1510–089, devised to shed light on this controversy. This paper presents its results, showing that, although microvariability was clearly detected in our three targets, no extremely violent optical variability event was detected along 110 h of observation. The largest fast flux variations we detected, instead, amount to  $\lesssim 0.1$  mag in about 1 h.

We show that this discrepancy is most likely due to systematic errors introduced during the observations and photometry. In particular, the use (without any correction) of stars much brighter than the target for differential photometry directly leads to an overestimation of the significance of any detected variability. Moreover, under certain specific conditions, it easily gives place to spurious variability closely reproducing extremely violent microvariability events as those reported in the papers by Xie and co-workers.

The following recommendations should thus be followed in order to prevent spurious variability results:

The target object must be neither underexposed nor saturated on all science frames. Differential light curves should be made using comparison and control stars as close in magnitude as possible to the target. Published standard stars in blazar fields are usually too bright for this purpose; they should be used just for calibration to the standard system, through a few short exposure-time frames.

If no suitable stars can be selected for differential photometry, brighter (or fainter) stars may be used, provided that the variance of the control–comparison light curve is properly scaled. This should be done following the method presented in HWM88 (in fact, it is *always* recommended to use HWM88 method).

Any remarkable flux change should be critically verified, looking for cosmic-ray hits, sudden changes in atmospheric transparency or any instrumental effect [see also Cellone et al. (2000) for spurious variability induced by seeing FWHM changes].

We conclude by saying that a critical evaluation of past and future claims for extremely violent microvariability events in blazars is needed before any radical revision of blazar models be required.

## ACKNOWLEDGMENTS

This work received financial support from ANPCyT (PICT03-13291 BID 1728/OC-AR) and CONICET (PIP 5375). Additional support from IALP (UNLP–CONICET) is also acknowledged. We thank Cecilia Fariña for help with the observations, and CASLEO staff members A. de Franceschi, R. Jakowczyk and P. Ostrov for their skilful assistance at the telescope. We wish to thank the anonymous referee for his/her very constructive comments.

## REFERENCES

Aller H. D., Aller M. F., Hodge P. E., 1981, *AJ*, 86, 325  
Aller M. F., Aller H. D., Hughes P. A., 1996, in Miller H. R., Webb J. R.,

Noble J. C., eds, ASP Conf. Ser. Vol. 110, *Blazar Continuum Variability Centimeter-wavelength Flux and Polarization Variability as a Probe of the Physical Conditions in AGN (I)*. Astron. Soc. Pac., San Francisco, p. 193  
Bai J. M., Xie G. Z., Li K. H., Zhang X., Liu W. W., 1998, *A&AS*, 132, 83  
Baumert J. H., 1980, *PASP*, 92, 156  
Carini M. T., Miller H. R., Goodrich B. D., 1990, *AJ*, 100, 347  
Carini M. T., Miller H. R., Noble J. C., Sadun A. C., 1991, *AJ*, 101, 1196  
Carini M. T., Miller H. R., Noble J. C., Goodrich B. D., 1992, *AJ*, 104, 15  
Carini M. T., Noble J. C., Miller H. R., 1998, *AJ*, 116, 2667  
Cellone S. A., Romero G. E., Combi J. A., 2000, *AJ*, 119, 1534  
Ciprini S., Tosti G., Raiteri C. M., Villata M., Ibrahimov M. A., Nucciarelli G., Lanteri L., 2003, *A&A*, 400, 487  
Dai B. Z., Xie G. Z., Li K. H., Zhou S. B., Liu W. W., Jiang Z. J., 2001, *AJ*, 122, 2901  
Dominici T. P., Abraham Z., Teixeira R., Benevides-Soares P., 2004, *AJ*, 128, 47  
Falomo R., Ulrich M.-H., 2000, *A&A*, 357, 91  
Falomo R., Bersanelli M., Bouchet P., Tanzi E. G., 1993, *AJ*, 106, 11  
Fan J. H., Lin R. G., 1999, *ApJS*, 121, 131  
Fan J. H., Lin R. G., 2000, *ApJ*, 537, 101  
Fuhmann L. et al., 2006, *A&A*, 445, L1  
Ghosh K. K., Ramsey B. D., Sadun A. C., Soundararajaperumal S., 2000, *ApJS*, 127, 11  
Gopal-Krishna, Wiita P. J., 1992, *A&A*, 259, 109  
Gopal-Krishna, Stalin C. S., Sagar R., Wiita P. J., 2003, *ApJ*, 586, L25  
Heidt J., Wagner S. J., 1996, *A&A*, 305, 42  
Howell S. B., 1989, *PASP*, 101, 616  
Howell S. B., Jacoby G. H., 1986, *PASP*, 98, 802  
Howell S. B., Warnock A. I., Mitchell K. J., 1988, *AJ*, 95, 247 (HWM88)  
Jang M., Miller H. R., 1997, *AJ*, 114, 565  
Liller M. H., Liller W., 1975, *ApJ*, 199, L133  
Lü P. K., 1972, *AJ*, 77, 829  
Mangalam A. V., Wiita P. J., 1993, *ApJ*, 406, 420  
Marscher A. P., 1992, in Zensus J. A., Wagner S. J., eds, *Physics of Active Galactic Nuclei Emission Models for Compact Jets*. Springer-Verlag, Heidelberg, p. 510  
Marscher A. P., Gear W. K., 1985, *ApJ*, 298, 114  
Miller H. R., Mullikin T. L., McGimsey B. Q., 1983, *AJ*, 88, 1301  
Miller H. R., Carini M. T., Goodrich B. D., 1989, *Nat*, 337, 627  
Mushotzky R., 2004, in Barger A. J., ed., *ASSL Vol. 308, Supermassive Black Holes in the Distant Universe*. Kluwer, Dordrecht, p. 53  
Nilsson K., Charles P. A., Pursimo T., Takalo L. O., Sillanpää A., Teerikorpi P., 1996, *A&A*, 314, 754  
Noble J. C., Miller H. R., 1996, in Miller H. R., Webb J. R., Noble J. C., eds, ASP Conf. Ser. Vol. 110, *Blazar Continuum Variability Extreme Optical Microvariability in Three Selected Blazars*. Astron. Soc. Pac., San Francisco, p. 30  
Puschell J. J., Stein W. A., 1980, *ApJ*, 237, 331  
Qian B., Tao J., 2003, *PASP*, 115, 490  
Rabbette M., McBreen S., Steel B., Smith N., 1996, *A&A*, 310, 1  
Racine R., 1970, *ApJ*, 159, L99  
Raiteri C. M. et al., 2005, *A&A*, 438, 39  
Raiteri C. M., Villata M., Lanteri L., Cavallone M., Sobrito G., 1998, *A&AS*, 130, 495  
Rector T. A., Stocke J. T., 2001, *AJ*, 122, 565  
Romero G. E., 1995, *Ap&SS*, 234, 49  
Romero G. E., Combi J. A., Vucetich H., 1995, *Ap&SS*, 225, 183  
Romero G. E., Cellone S. A., Combi J. A., 1999, *A&AS*, 135, 477  
Romero G. E., Cellone S. A., Combi J. A., 2000a, *A&A*, 360, L47  
Romero G. E., Cellone S. A., Combi J. A., 2000b, *AJ*, 120, 1192  
Romero G. E., Cellone S. A., Combi J. A., Andruchow I., 2002, *A&A*, 390, 431  
Sagar R., Stalin C. S., Gopal-Krishna G., Wiita P. J., 2004, *MNRAS*, 348, 176  
Singh K. P., Shrader C. R., George I. M., 1997, *ApJ*, 491, 515  
Sreekumar P. et al., 1996, *ApJ*, 464, 628

- Stalin C. S., Gupta A. C., Gopal-Krishna, Wiita P. J., Sagar R., 2005, MNRAS, 356, 607
- Tanzi E. G. et al., 1986, ApJ, 311, L13
- Thompson D. J. et al., 1993, ApJ, 415, L13
- Villata M. et al., 1997, A&AS, 121, 119
- Villata M., Raiteri C. M., Lanteri L., Sobrito G., Cavallone M., 1998, A&AS, 130, 305
- Wu J., Zhou X., Peng B., Ma J., Jiang Z., Chen J., 2005, MNRAS, 361, 155
- Xie G. Z., Li K. H., Zhang X., Bai J. M., Liu W. W., 1999, ApJ, 522, 846
- Xie G. Z., Li K. H., Bai J. M., Dai B. Z., Liu W. W., Zhang X., Xing S. Y., 2001, ApJ, 548, 200
- Xie G. Z., Liang E. W., Zhou S. B., Li K. H., Dai B. Z., Ma L., 2002a, MNRAS, 334, 459
- Xie G. Z., Zhou S. B., Dai B. Z., Liang E. W., Li K. H., Bai J. M., Xing S. Y., Liu W. W., 2002b, MNRAS, 329, 689
- Xie G. Z., Zhou S. B., Li K. H., Dai H., Chen L. E., Ma L., 2004, MNRAS, 348, 831

This paper has been typeset from a  $\text{\TeX}/\text{\LaTeX}$  file prepared by the author.