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Unusual optical quiescence of the classical BL Lac object PKS 0735+178 on intranight time scale

Arti Goyal[1⋆], Gopal-Krishna[2], G. C. Anupama[3], D. K. Sahu[3], R. Sagar[1], S. Britzen[4], M. Karouzos[4]†, M. F. Aller[5], H. D. Aller[5]

[1] *Aryabhatta Research Institute of observational sciencES (ARIES), Manora Peak, Naini Tal 263 129, India*

[2] *NCRA.TIFR, Pune University Campus, Pune 411 007, India*

[3] *Indian Institute of Astrophysics (IIA) Bangalore 560 034, India*

[4] *Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany*

[5] *Astronomy Department, University of Michigan, Dennison Building, Ann Arbor, MI 48109-1090, USA*

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ABSTRACT

We present the result of our extensive intranight optical monitoring of the well known low-energy peaked BL Lac (LBL) object PKS 0735+178. This long-term follow-up consists of R-band monitoring for a minimum duration of ~ 4 hours, on 17 nights spanning 11 years (1998-2008). Using the CCD as an N-star photometer, a detection limit of around 1% was attained for the intranight optical variability (INOV). Remarkably, an INOV amplitude of $\geqslant 3\%$ on hour-like time scale was not observed on any of the 17 nights, even though the likelihood of a typical LBL showing such INOV levels in a single session of $\gtrsim 4$ hours duration is known to be high ($\sim 50\%$). Our observations have thus established a peculiar long-term INOV quiescence of this radio-selected BL Lac object. Moreover, the access to unpublished optical monitoring data of similarly high sensitivity, acquired in another programme, has allowed us to confirm the same anomalous INOV quiescence of this LBL all the way back to 1989, the epoch of its historically largest radio outburst. Here, we present observational evidence revealing the very unusual INOV behaviour of this classical BL Lac object and discuss this briefly in the context of its other known exceptional properties.

Key words: BL Lac objects – general - individual : PKS 0735+178 – variability – intranight – optical: Galaxies - active – Galaxies - jets

1 INTRODUCTION

Characterized by extreme faintness or absence of broad emission lines in their optical/UV spectra, BL Lac objects are a subset of the *blazar* population for which the dominant source of emission is believed to be a relativistic jet of non-thermal radiation (e.g., Blandford & Rees 1978; Urry & Padovani 1995). A key optical property of blazars is large and frequently occuring rapid flux variability (also termed as INOV), which is not exhibited by other radio-loud or radio-quiet active galactic nuclei (AGN). Thus, a classical, radio-selected BL lac object (RBL), when monitored continuously for more than about 4 hours, is quite likely to show optical variability at the level of a few percent, on hour-like time scale (e.g., Miller, Carini & Goodrich 1989; Wagner & Witzel 1995; Romero et al. 2002). More specifically, INOV amplitude $\psi > 3\%$ is expected to occur in such observations, with a probability (duty cycle: DC) of $\sim 53\%$ (Gopal-Krishna et al. 2003; Stalin et al. 2005). A similar estimate (DC $\sim 57\%$) is obtained using the data from an independent programme of intranight monitoring of a well defined sample of EGRET detected RBLs (see Table 1 of Romero et al. 2002). For X-ray selected blazars (XBLs), the INOV duty cycle is about two times smaller (Romero et al. 2002; also, Heidt et al. 1998). Recall that the above estimates for RBLs are based on light curves of durations longer than 4 hours and therefore, for consistency, we shall stick to the same criterion while selecting any intranight light curves from the literature for the purpose of making statistical comparisons.

Since recent studies (Stalin et al. 2005; Gopal-Krishna et al. 2003) have shown that large amplitude INOV ($\psi > 3\%$) is displayed exclusively by blazars, i.e., BL Lacs and Highly Polarized Quasars (HPQs), such INOV is generally expected to be primarily associated with the relativistic jet. Yet, the precise mechanism of the INOV remains obscure. The possibilities often invoked include perturbations in the inner jet, caused by shear or relativistic shocks, small-scale inhomogeneities in the magnetic field and instabilities in the particle acceleration, etc. (e.g., Wiita 1996; Marscher 1996 and references therein). Some contribution

⋆ E-mail: arti@aries.res.in
† Member of the International Max Planck Research School (IMPRS) for Astronomy and Astrophysics at the Universities of Bonn and Cologne

to INOV can also be expected from accretion disk instabilities (Mangalam & Wiita 1993) and, occasionally, from "superluminal gravitational microlensing" (Gopal-Krishna & Subramanian 1991; also, Rabbette et al. 1996; Romero, Surpi & Vucetich. 1995). Potential clues for assessing the relative importance of these various mechanisms may emerge by identifying and then studying in detail blazars exhibiting some highly unusual pattern of INOV.

During the ARIES programme of optical monitoring of a sample of powerful AGN, the well known RBL, PKS 0735+178, was found to exhibit remarkably low-level INOV ($\psi <\sim 1\%$) on all the 4 nights it was monitored during 1998-2001 (Sagar et al. 2004). To probe this unexpected result, we have extended intranight monitoring of this RBL for a further seven years. This has yielded its intranight R-band differential light curves (DLCs) for a total of 17 nights, between 1998 and 2008. Thus, the DLCs are available for minimum one night every winter since 1998, except for 2002. Each DLC is longer than ~ 4 hours and has a sensitivity adequate for a secure detection of INOV down to $1-2\%$ level. In this paper, we report these new data and discuss our entire dataset in the broader context of the published multi-wavelength observations of this well known BL Lac object.

PKS 0735+178 is among the first sources to be designated as "classical BL Lac" (Carswell et al. 1974). Its host galaxy still remains unresolved (e.g., Pursimo et al. 2002) but an absorption feature in the optical spectrum, identified as Mg-II, has yielded a lower redshift limit of $z > 0.424$ (e.g., Rector & Stocke 2001). Hartman et al. (1999) have reported $\gamma-$ray detection of this blazar using EGRET. On the basis of its spectral energy distribution peaking at 10^{13-14} Hz, it can be confidently classified as a 'low energy peaked' BL Lac (LBL) (Padovani et al. 2006; Nieppola, Tornikoski & Valtaoja 2006; Ghisellini, Tavecchio & Chiaberge 2005). Whereas in the optical and even in the radio band PKS 0735+178 has shown strong variability (Webb et al. 1988; Ciprini et al. 2007; Qian & Tao 2004; Fig. 1; Sect. 4) characteristic of blazars, its X-ray and $\gamma-$ray emission was found to be quite steady (Bregman et al. 1984; Madejski & Schwarz 1988; Nolan et al. 2003). Specifically, based on their analysis of the Einstein Observatory (IPC) observations from April, 1979 till March, 1981, Madejski & Schwarz (1988) found no deviation from the mean flux density at ~ 1 keV, by more than 20%, on time scales between several hours to 2 years. Thus, they concluded that "the lack of variability in PKS 0735+178 is exceptional among BL Lac objects" (Sect. IIb of their paper). In contrast, its optical flux more than doubled during the same period (Fig. 1b). Another curious early finding was its remarkably smooth flat radio spectrum, which was interpreted as the superposition of many homogeneous components of incoherent synchrotron radiation, so called “cosmic conspiracy” (Cotton et al. 1980).

2 OBSERVATIONS AND DATA REDUCTION

The photometric observations were carried out using the 104-cm Sampurnanand telescope (ST) located at Aryabhatta Research Institute of observational sciencES (ARIES), Naini Tal (India), except on one night when the 201-cm Himalayan Chandra telescope (HCT) of IAO at Hanle (India) was used. ST has a Ritchey-Chretien (RC) optics with a f/13 beam (Sagar 1999). The detector was a cryogenically cooled 2048 $\times$ 2048 chip mounted at the Cassegrain focus. This chip has a readout noise of 5.3 e^-/pixel and a gain of 10 e^-/Analog to Digital Unit (ADU) in an usually employed slow readout mode. Each pixel has a dimension of 24 μm^2 which corresponds to 0.37 arcsec^2 on the sky, covering a total field of $13' \times 13'$. Observations were carried out in 2 $\times$ 2 binned mode to improve the S/N ratio. The seeing mostly ranged between $\sim 1.5''$ to $\sim 3''$, as determined using three moderately bright stars recorded along with the blazar on the same CCD frame (Fig. 2).

The HCT is located at the Indian Astronomical Observatory (IAO), Hanle (Ladakh) in northern India. It is also of the RC design with a f/9 beam at the Cassegrain focus[1]. The detector was a cryogenically cooled 2048 $\times$ 4096 chip, of which the central 2048 $\times$ 2048 pixels were used. The pixel size is 15 μm^2 so that the image scale of 0.29 arcsec/pixel covers an area of $10' \times 10'$ on the sky. The readout noise of CCD is 4.87 e^-/pixel and the gain is 1.22 e^-/ADU. The CCD was used in an unbinned mode.

All the observations were carried out using R filter for which the CCDs used have maximum sensitivity. The exposure time was typically 12-30 minutes for the ST and about 3 minutes for the HCT observations. The field positioning was adjusted so as to also include within the CCD frame at least 2-3 comparison stars within about a magnitude of the blazar, in order to minimize the possibility of spurious variability detection (see, e.g., Cellone, Romero & Araudo 2007). For both the telescopes, the bias frames were taken intermittently and twilight sky flats were obtained. Table 1 gives the log of our observations of this blazar, including those already reported in Sagar et al. (2004). The data provided include for each observation the date, the telescope used, number of data points in the DLC,

[1] http://www.iiap.res.in/∼iao

the total duration of monitoring, the quantifiers of INOV, C_{eff} and the amplitude ψ (Sect. 3) as well as a remark on the INOV status.

The preprocessing of the CCD images (i.e. bias subtraction, flat-fielding and cosmic-ray removal) was done following the standard procedures in IRAF[2] and MIDAS[3] packages. The instrumental magnitudes of the blazar and the stars in the image frames were determined by aperture photometry, using DAOPHOT II[4] (Stetson 1987). The magnitudes of the blazar were measured relative to the nearby comparison stars present on the same CCD frame in order to account for the extinction of blazar's light due to the earth's atmosphere. This way, Differential Light Curves (DLCs) of the blazar were generated relative to three comparison stars. Likewise, DLCs were also generated for each comparison star relative to the other two comparison stars. For each night, the selection of the optimum aperture radius for photometry was done on the basis of the observed dispersions in the star-star DLCs generated using different aperture radii, starting from the median seeing (FWHM) value on that night to 4 times that value. The aperture selected was the one which showed minimum scatter for the steadiest DLC found for the various pairs of the comparison stars. The selected aperture radius was then used to generate DLCs for the target blazar relative to the comparison stars, as well as for the individual comparison stars, by pairing them with the remaining two comparison stars. The 'seeing' was monitored throughout the night using three moderately bright stars recorded in each CCD frame. Additional details of the data reduction procedure can be found in Stalin et al. (2004, 2005).

3 RESULTS

Figure 2 shows our newly obtained intranight DLCs for PKS 0735+178 and the comparison stars, along with the plots of 'seeing', as described above. By combining these with the DLCs for the four nights, published in Sagar et al. (2004), we have generated 'long-term (differential) light curve', relative to the *same* set of comparison stars as used by Sagar et al. (2004), thus maintaining continuity in the long-term optical DLC (Fig. 3). **The optical field of PKS 0735+178, marking the blazar and the comparison stars used by us, is shown in Figure 4.** The long-term DLC exhibits a peak-to-peak variation of $\sim$1.7 mag (Fig. 3). We have also transformed these differential light curves into actual light curves,

[2] Image Reduction and Analysis Facility
[3] Munich Image and Data Analysis System
[4] Dominion Astrophysical Observatory Photometry software

by computing the average instrumental magnitude for each of those nights and calibrating those values using at least two standard stars available on the CCD frames, after ensuring that they had remained unsaturated throughout the monitoring. The standard stars used are: C7 and D (as given by Ciprini et al. 2007). The calibrated LTOV data points are plotted in Fig. 1a.

Based on the intranight DLCs (Fig. 2), we have determined the INOV status and the INOV amplitude (ψ) for each night, as given in Table 1. Table 2 lists the positions and apparent magnitudes of the comparison stars used in producing the INOV and LTOV differential light curves (Figs. 2 & 3). The INOV classification 'variable' (V) or 'non-variable' (N) was decided using a computed parameter C_{eff}, basically following the criteria of Jang & Miller (1997). We define C for a given DLC as the ratio of its standard deviation, σ_T and $\eta\sigma_{err}$, where σ_{err} is the average of the rms errors of its individual data points and η was estimated to be 1.5 (Stalin et al. 2004, 2005; Gopal-Krishna et al. 2003; Sagar et al. 2004). However, our analysis for the present dataset yields $\eta = 1.3$ which we have used here. We finally computed C_{eff} for a given observing session, using the C values (as defined above) determined for the DLCs of the blazar relative to different comparison stars monitored during that session (for details, see Sagar et al. 2004). This procedure has the advantage of utilizing the multiple DLCs of an AGN available during a single session (i.e., relative to different comparison stars). The source is termed 'V' if $C_{eff} > 2.57$, corresponding to a confidence level of 99%. We call the AGN to be 'probable variable' (PV) if C_{eff} is found to be in range of 1.95 to 2.57, corresponding to a confidence level between 95% to 99%. Finally, the peak-to-peak INOV amplitude (ψ) was calculated using the definition (Romero, Cellone & Combi 1999):

$$\psi = \sqrt{(D_{max} - D_{min})^2 - 2\sigma^2} \qquad (1)$$

with

D_{max} = maximum in the AGN differential light curve

D_{min} = minimum in the AGN differential light curve

$\sigma^2 = \eta^2 \langle \sigma^2_{err} \rangle$

The INOV duty cycle (DC) for PKS 0735+178 was computed using our entire dataset of 17 nights, following the definition of Romero, Cellone & Combi (1999) (see, also, Stalin et al. 2004):

$$DC = 100\frac{\sum_{i=1}^{n} N_i(1/\Delta t_i)}{\sum_{i=1}^{n}(1/\Delta t_i)}\% \quad (2)$$

where $\Delta t_i = \Delta t_{i,obs}(1+z)^{-1}$ is the duration of monitoring session of a source on the ith night, corrected for the blazar's cosmological redshift z. Note that since the source was not monitored for identical duration on each night, the computation has been weighted by the actual duration of monitoring Δt_i. N_i was set equal to 1 if INOV was detected, otherwise $N_i = 0$.

DC is found to be $\sim 27\%$, which increases to $\sim 42\%$ if the two cases of probable INOV are also included. The key result, however, is that *large INOV ($\psi \geqslant 3\%$) was consistently absent on all the 17 nights*, even though the data quality remained adequate throughout.

4 SUMMARY OF THE VARIABILITY PATTERNS

In this section we summarize the complex flux variability patterns exhibited by this blazar, in order to focus attention on both its normal and anomalous aspects. Such a background perspective is important for appreciating its rather surprising INOV behavior established in this work.

4.1 Long-term optical variability

Recently, Ciprini et al. (2007) have published a long-term B-band light curve of PKS 0735+178, spanning almost 100 years (1906 - 2004) (see, also Fan et al. 1997). Of this, the best sampled segment covers the last 33 years (867 nights, 1970 onwards). In Fig. 1b we reproduce the light curve[5], taking median of the data binned into successive one-year intervals. Starting from Feb., 1993, the data given in Ciprini et al. (2007) are based on CCD monitoring ($BVRI$), with the densest sampling attained in the R-band. Again, we have taken the medians for successive 1-year bins and augmented those data with our own R-band measurements for the period 1998-2008, after converting the calibrated magnitudes to flux densities and averaging over each night (Sect. 3). The composite R-band light curve for the period 1993-2008 is shown in Fig. 1a. It is found that the blazar's optical flux dropped close to the historical minimum (occuring in early 1997), at the epoch 2007.0 from where it doubled by the end of 2007 and then dropped back in 2008 to a level close to the historical

[5] Data points were retrieved from Fig. 4 [lower panel] of Ciprini et al. (2007) using the standalone version of a programme *Dexter* (http://vo.uni-hd.de/dexter/ui/ui/custom) available over SAO/NASA ADS by Demleitner et al. (2001).

minimum. Considerably more pronounced optical variability was recorded during the previous 7 years (Fig. 1a). Fig. 2 of Ciprini et al. (2007) shows typical variations of about 1 mag on time intervals smaller than 1/2 year (see below), which together with the dominant radio core (see Sect. 1) is consistent with its being a LBL type BL Lac (e.g., Lister & Smith 2000).

The 100-year optical light curve of PKS 0735+178 shows five optical outbursts, with the historical maximum (B $\sim$ 13.9 mag) reached in mid-1977 (Ciprini et al. 2007). The last major outburst occurred around mid-2001 (B $\sim$ 15.0 mag), following the historical minimum (B $\sim$17.5 mag) in early 1997. Ciprini et al. (2007) have identified three main temporal components in the light curve: $\sim$ 4.5 yr, $\sim$ 8.5 yr and $\sim$ 12 yr. The shortest of these characteristic time scales had earlier been noted by Webb et al. (1988) and by Smith & Nair (1995), whereas the intermediate time scale was inferred previously by Qian & Tao (2004). Ciprini et al. (2007) have suggested that these three characteristic time scales may well be harmonic signatures of one fundamental component of about 4 years. Note that the optical spectral index (α_o; defined as $S_\nu \propto \nu^{-\alpha}$) given by Ciprini et al. (2007) for the data set 1993-2004 did not show any correlation with the fluctuations in the light curve (upper panel of their Fig. 5) and has remained steady with an average value of 1.25 ± 0.15, indicating an essentially achromatic optical variability. However, a rather weak positive correlation between the color index and the flux was noticed in the study conducted by Gu et al. (2006) covering a total of 50 nights (between Sept. 2003 - Feb. 2004), when source became bluer with increasing brightness (see, also, Hu et al. 2006).

4.2 Long-term radio variability

Since around 1979, PKS 0735+178 has been regularly monitored at 5, 8 and 15 GHz using the 26-metre Michigan dish. The observing technique, calibration procedures and instrumentation are described elsewhere (see, Aller et al. 1985; 1999). The UMRAO light curves at 15 and 5 GHz are plotted in Figures 1c & 1d. Figure 1e shows the run of spectral index (defined as $S_\nu \propto \nu^a$) calculated by a linear regression analysis of the flux values at the three frequencies (Note that measurements at these frequencies were treated as simultaneous and hence combined only provided they are separated by no more than $q = 0.04$ year). Figure 1f shows the variation of the percentage (linear) polarization at 15 GHz. The monitoring of this blazar at still higher frequencies of 22 GHz and 37 GHz has been carried out using the

13.7-metre Matsähovi antenna and the light curve for the period $\sim$ 1981 - 2004 is displayed in Fig. 1 of Teräsranta et al. (2005). After a gradual decline from 1981 till 1987, the blazar displayed a large outburst when its flux at 37 GHz jumped from $\sim$1 Jy to $\sim$5 Jy. A second flare of comparable amplitude occured soon, following which the flux declined to $\sim$ 1.5 Jy by 1994.0. After the 'twin radio flares', only mild variability has been observed. All these trends are closely mirrored in the UMRAO light curves at 15, 8 and 5 GHz (Fig. 1c & d). From a comparison of the light curves at 5, 8, 15, 22 and 37 GHz, it is evident that the first of the twin radio flares has a flatter spectrum (i.e., a greater synchrotron opacity). Interestingly, the pattern of the radio light curves is closely mimicked by the run of radio spectral index (α_r).

Although a general increase in optical variability was noticed during the large radio outburst of 1987-1997 (Fig. 1b), no clear optical counterpart to that radio outburst is evident from the data (Hanski et al. 2002; Tornikoski et al. 1994; Clements et al. 1995). In contrast, correlated flaring at optical and radio bands is known to be much more common for BL Lacs than for flat-spectrum radio quasars (FSRQs), suggesting that synchrotron opacity of the nuclear jet may be modest for the BL Lacs (Clements et al. 1995).

4.3 Optical and radio polarization variability

Characteristic of BL Lac objects, PKS 0735+178 has shown a large long-term variability of optical (linear) polarization, from about 1% to more than 30% (Tommasi et al. 2001). However, on day-like or shorter time scales, covered in their polarimetric observations on four nights (Dec. 10, 11, 12 and 14, 1999), optical polarization remained steady at $\sim$ 10%, though a modest variability in the position angle was seen on internight and even intranight time scale. Thus, while the high polarization does signify the active state of this blazar, the preferred polarization angle found over a few years (Tommasi et al. 2001) appears to manifest a state of stability in the optically emitting structures within the jet (Ciprini et al. 2007). Note that a modest degree of optial polarization ($\sim$ 4%) was measured in the observations of this LBL on Feb., 8, 2008 (Villforth et al. 2009).

The UMRAO time series of fractional (linear) polarization at 15 GHz, covering the period since 1981, is shown in Fig. 1f. Typically, the integrated polarization has remained between 2% and 4%, although near the first peak of the twin radio flares in mid-1989, the 15 GHz polarization rose to 5% - 6% level. Note that radio polarization at a few percent level with typical maximum value $< 10\%$, is a common occurrence for BL Lac objects (Aller et al. 1999). Correlation between the emergence of new VLBI component and the radio flaring has been reported by many authors (e.g., Wagner et al. 1995; Wehrle , Pian & Urry 1998) and usually these superluminal knots are substantially polarized (Gabuzda & Cowthorne 1996; Lister, Marscher & Gear 1998; Gòmez, Marscher & Alberdi 1999). Further, the study by Jorstad et al. (2001) has found that $\gamma-$ray flares are correlated with the emergence of new VLBI components, which is usually explained in terms of the standard model where the VLBI components are the manifestations of a relativistic shock propagating through an underlying relativistic outflow (e.g., Marscher et al. 2008; see, also, Krichbaum et al. 1995).

4.4 The variable compact radio jet

Typical of blazars, the dominant radio core of PKS 0735+178 is surrounded by a $\sim 10''$ radio 'halo' (Cassaro et al. 1999). Its (unbeamed) luminosity is at least an order-of-magnitude above the Fanaroff-Riley transition, placing it in the Fanaroff-Riley class II (Fanaroff & Riley 1974). A steep-spectrum radio jet of length $\sim 2''$ is seen to extend from the core at position angle (PA) $\sim 160°$ (Tingay et al. 1998). The core has been the target of many VLBI campaigns (e.g., Agudo et al. 2006 and references therein). Multi-epoch VLBI imaging at 8, 22 and 43 GHz at several epochs from mid-1996 to mid-1998 revealed two peculiar sharp bends within the inner 2 milli arcsec (~ 11 parsec) of the jet (Gòmez et al. 1999; 2001; see, also, Kellermann et al. 1998). The consistency between these images and several previously reported, lower-resolution VLBI images taken during mid-1995, suggests that the two bends were present already in mid-1995 (Gòmez et al. 2001 and references therein). Intriguingly, this feature was absent in the VLBI images taken during the several years preceding mid-1992. The jet was then found to be rectilinear extending at PA $\sim 65°$ (Bååth & Zhang 1991; Gabuzda, Wardle & Roberts 1989) and some of its knots exhibited large superluminal speeds ($7c - 12c$) (e.g., Gabuzda et al. 1994; Gòmez et al. 2001 and references therein). Thus, sometime between mid-1992 and mid-1995, the blazar appears to have undergone a change into a regime characterized by quasi-stationary VLBI knots in the jet (Gòmez et al. 2001; Agudo et al. 2006). Note that the "transition epoch" coincided with a huge decline in the radio flux that continued till 1998 (Fig. 1c & d). The sharp bends in the VLBI jet were probably caused by gas pressure gradients on 10-parsec scale within the nuclear region, since the magnetic field follows the jet curvature, thus supporting the notion of (non-ballistic) fluid motion along the jet during that phase (Gòmez et al. 1999).

Beginning with the year 2000, a resumption in the nuclear activity in this blazar is manifested firstly by the upturn in its optical light curve (Fig. 1a) and, secondly, by the near doubling of its 15 GHz flux density between mid-2000 and end-2002 (Fig. 1c & d). Interestingly, during the same period, the 15 GHz *MOJAVE* VLBI image (taken on 23 November 2002, Lister & Homan 2005) found the jet to be fairly rectilinear and no longer exhibiting the double-bend witnessed during 1995 - 2000 within 3 milli arcsecond from core (e.g., see the 5 and 43 GHz VLBI images made by Agudo et al. 2006; also, Kellermann et al. 2004). The 'straightened' VLBI jet with PA $\sim 59 - 84^{\circ}$, as inferred from the all five components found within 11 parsec from the core, is extremely mis-aligned from the kilo-parsec scale jet that extends at PA $\sim 105^{\circ}$ (Tingay et al. 1998). Large misalignment between the jets on parsec and kilo-parsec scales is indeed quite common for LBL type BL Lac objects (Britzen et al. 2007 and references therein).

5 DISCUSSION

In December 1998 when we embarked on the intranight optical monitoring of PKS 0735+178, the R-band flux of this BL Lac had risen three-fold during the preceding year, from the historical minimum of 0.6 mJy to $\sim$ 2 mJy (Fig. 1a). By December 2001, the source had further brightened, forming a local peak of $\sim$ 6 mJy which is only $\sim$ 3 times lower than the historical maximum attained by this blazar (Ciprini et al. 2007). Thus, the last decennium has witnessed a ten-fold change in the optical (synchrotron) flux. The factor would be even larger if the thermal accretion disk contributed significantly near the brightness minimum. In any event, the time span covered in our INOV monitoring witnessed a minimum three-fold rise in the optical synchrotron flux, followed by a similar amount of fading. Thus, in terms of its jet emission, the blazar cannot be deemed to have been quiescent during the decennium spanned by our monitoring programme. It is in this setting that a closer scrutiny of the INOV behavior of this blazar and of its multi-band continuum and polarization properties is called for.

As seen from Table 1, PKS 0735+178 showed INOV on 4 out of the total 17 nights it was monitored in our programme. This corresponds to a INOV duty cycle DC = 27% (see Sect. 3). Over these eleven years, the optical flux recorded a peak-to-peak amplitude variation of slightly over 1.7 mag (Fig. 3). Our data (Table 1) provide a hint that the nights of INOV detection coincide not with the extrema but with gradients in optical flux, consistent with the trend noted by Webb et al. (1998) and Howard et al. (2004). However, we caution that such a correlation is weak, at best, since the INOV detections were marginal.

The key result from our observations is that not even on one of the 17 nights was the INOV amplitude of this BL Lac found to be $> 3\%$, even though the probability of observing such INOV amplitudes is known to be $\sim 50\%$ in any single monitoring session longer than ~ 4 hours, a condition that was well satisfied in our programme (Sect. 1; Table 1). The probability of our negative result arising purely by chance is vanishingly small $< 7.6 \times 10^{-6}$. This suggests that PKS 0735+178 has persisted in an INOV quiescent state since 1998, despite other indications of its returning to an active state during this period. As summarized in Sect. 4, the indicators of renewed activity include (a) the large variation in its optical synchrotron flux on month/year-like time scale and (b) the return of its VLBI jet to the 'normal' rectilinear shape. Other indicators of a typical blazar state are the fairly high degrees of optical and radio polarization (Sect. 4.3) and the persistence of its flat radio spectrum (Fig. 1e). On the other hand, a rather uncharacteristic behaviour is echoed by the fact that during the past two decades this blazar has undergone large radio outburst just once (Sect. 4.2; also, Hovatta et al. 2007) and that too without a clear optical counterpart (Sect. 4.3). Furthermore, its X-ray/$\gamma-$ray emission has been fairly steady (Sect. 1).

Here we note that recently from their 4-hour long R-band monitoring of this blazar on Jan. 11, 2007 at Yunnan Observatory, Gupta et al. (2008) have reported an INOV detection. However, since their published DLC (Fig. 6 of their paper) is essentially flat and contains no significant structure on hour-like time scale, the INOV claimed by them can at best be of 'flicker' type, with a time scale much shorter than the hour-like time scale we have considered here.

In order to augment the present study we now turn attention to the (unpublished) optical monitoring data reported in Tables 3.1 and 4.1 of Dr. John Noble's PhD dissertation (1995). During Jan. 25 - 31, 1992 he monitored PKS 0735+178 on 6 nights in R-band, using the 1.07-metre Lowell telescope. On 5 of the nights, the monitoring duration was sufficiently long to meet our criterion (6.7, 3.9, 4.2, 5.0 and 8.2 hours) and so also was the sensitivity of the DLCs ($\sigma \leqslant 1\%$) (Sect. 1). Remarkably, on just one of these five nights did the blazar show INOV and that too with an amplitude of only 2% (Table 4.1). This trend of INOV quiesence is further corroborated by Noble's 5 hour long V-band monitoring of this blazar on March 17, 1989, using the KPNO 0.9-metre telescope. Again, no INOV was detected, despite the high sensitivity attained ($\sigma = 1\%$). All these results place on a stronger footing the finding already emerging from our 17 nights' monitoring during 1998-2008 (Table 1), namely that this *bona-fide* radio selected BL Lac is quite exceptional for its propensity to remain in a state of intranight optical quiescence (i.e., $\psi \leqslant 3\%$). Here it needs to be emphasized that, unlike our optical observations over the period 1998-2008, during which the radio flux of PKS0735+178 was still at a comparatively low level (despite a resumption in its optical activity), the afore-mentioned optical data of Noble (1995) are actually contemporaneous to the historically strongest radio outburst (Fig. 1c & d). Thus, while his March 1989 observations coincided with the first of the twin radio flares (the historical maximum), his 5 nights' monitoring during Jan. 1992 coincided with the onset of decline of the second peak of the twin radio flare (Fig. 1c & d).

Since substantial optical variability on wide ranging time scales, which is typical of blazars, is commonly associated with shocks forming and interacting with inhomogeneities in the Doppler boosted synchrotron jets (e.g., Marscher, Gear & Travis 1992), it is tempting to ask if the prolonged uncharacteristically subdued INOV level of the classical blazar PKS 0735+178 is a manifestation of some unusual property of its jet. One model that explicitly attempts to address this question, particularly in the context of hour-like or shorter time scales of variability, invokes interaction of relativistic shocks in the jet with sub-parsec scale irregularities (Romero 1995). This scenario has been developed specifically for the two-fluid model of AGN jets originally proposed by Sol et al. (1989), wherein an extremely light and narrow beam of relativistic pair-plasma responsible for the apparent superluminal motion in the nuclear jets, is enveloped by a wider jet comprised of a much denser non-relativistic electron-proton plasma which carries most of the kinetic energy and terminates in kiloparsec sized hot spots (Pelletier & Roland 1989; Henri & Pelletier 1991). It has been argued that sub-parsec scale irregularities (needed for INOV) could arise in the beam of such jets due to classical macroscopic Kelvin-Helmholtz instabilties, in case the axial magnetic field in the beam, B_z, is below a critical value $B_c = [4\pi n_b m_e c^2(\gamma_b^2 - 1)]^{1/2}\gamma_b^{-1}$, where n_b and γ_b are the electron number density and bulk Lorentz factor of the beam, respectively and m_e is the electron rest mass (Romero 1995). Applying this model to the case of the well studied intraday variable blazar 0917+624, for

which estimates of the beam's density and magnetic field are available, Romero has shown that for a highly supersonic beam flow and equipartition magnetic fields, the (fastest growing) reflection modes would cross over into the unstable regime and a rapid transition to a turbulent jet would occur, yielding the basic setting for INOV. Although estimates for the basic physical parameters for the present LBL PKS 0735+178 are not available, it is conceivable that its beam is fairly stable to the K-H instabilities (i.e., $B_z > B_c$**, see above). Such a prospect is indeed supported by the polarimetric VLBI data revealing that the magnetic field in the nuclear jet of this LBL is predominently axial (Agudo et al. 2001), unlike the norm for such BL Lacs (e.g., Lister & Homan 2005 ; Kharb, Gabuzda & Shastri 2008).**

It is clear that in order to develop a proper understanding of the anomalous INOV behaviour of PKS 0735+178, clues will have to be gleaned by relating its multi-band variability patterns (of which some are distinctly typical of BL Lacs, while the others are less so, see above) to the VLBI imaging and polarimetry of its nuclear jet. The VLBI observations have already revealed enigmatic multiple twists in the nuclear jet which are transitory, like the superluminal motion of its radio knots (Sect. 4). Could the processes underlying this peculiar behaviour have kept the inner jet (where INOV presumably originates) hidden from our view ? These aspects will be examined by us elsewhere (**Britzen et al. 2009, in prep.**), based on an available sequence of VLBI images of this blazar taken at more than 20 epochs over the past two decades.

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Table 1. The observation log and INOV results for PKS 0735+178.

Date dd.mm.yy	Telescopes used	Number of points	Duration (hours)	ψ (%)	C_{eff}	Status‡	References
26.12.98	ST	49	7.8	1.8	1.13	N	Sagar et al. (2004)
30.12.99	ST	64	7.4	1.0	0.61	N	Sagar et al. (2004)
25.12.00	ST	42	6.0	1.6	1.02	N	Sagar et al. (2004)
25.12.01	ST	43	7.3	1.0	2.8	V	Sagar et al. (2004)
20.12.03	HCT	36	5.8	1.0	1.78	N	present work
10.12.04	ST	28	5.8	1.3	3.00	V	present work
23.12.04	ST	11	5.0	1.2	3.10	V	present work
02.01.05	ST	20	4.9	0.8	0.97	N	present work
05.01.05	ST	23	5.8	1.0	2.25	PV	present work
09.01.05	ST	28	6.7	1.3	3.20	V	present work
09.11.05	ST	17	3.8	0.7	2.00	PV	present work
16.11.06	ST	19	4.5	1.1	0.95	N	present work
29.11.06	ST	26	5.8	1.0	0.83	N	present work
17.12.06	ST	24	5.6	0.9	1.06	N	present work
15.12.07	ST	28	6.6	1.9	3.53	V	present work
16.12.07	ST	27	6.6	1.0	1.45	N	present work
22.11.08	ST	27	5.6	0.8	0.33	N	present work

‡V = variable; N = non-variable; PV = probable variable

Table 2. Positions and apparent magnitudes of the comparison stars used in the present study (taken from United States Naval Observatory-B catalogue; Monet et al. 2003)

Star	RA(J2000)	Dec(J2000)	B (mag)	R (mag)	B-R (mag)
S1	$07^h37^m48^s.21$	$+17°40'14''.4$	16.05	14.86	1.19
S2	$07^h38^m12^s.15$	$+17°38'07''.3$	15.62	15.25	0.37
S3	$07^h37^m48^s.88$	$+17°41'30''.4$	16.23	15.26	0.97
S4	$07^h38^m26^s.00$	$+17°40'22''.5$	16.15	15.55	0.60
S5	$07^h38^m13^s.82$	$+17°38'22''.8$	15.29	14.68	0.61
S6	$07^h38^m08^s.35$	$+17°44'59''.3$	15.94	15.59	0.35
SS1	$07^h38^m03^s.42$	$+17°42'55''.8$	16.48	15.89	0.59
SS2	$07^h38^m17^s.08$	$+17°39'03''.6$	16.29	15.96	0.33
SS3	$07^h38^m10^s.26$	$+17°43'43''.8$	16.71	16.46	0.25

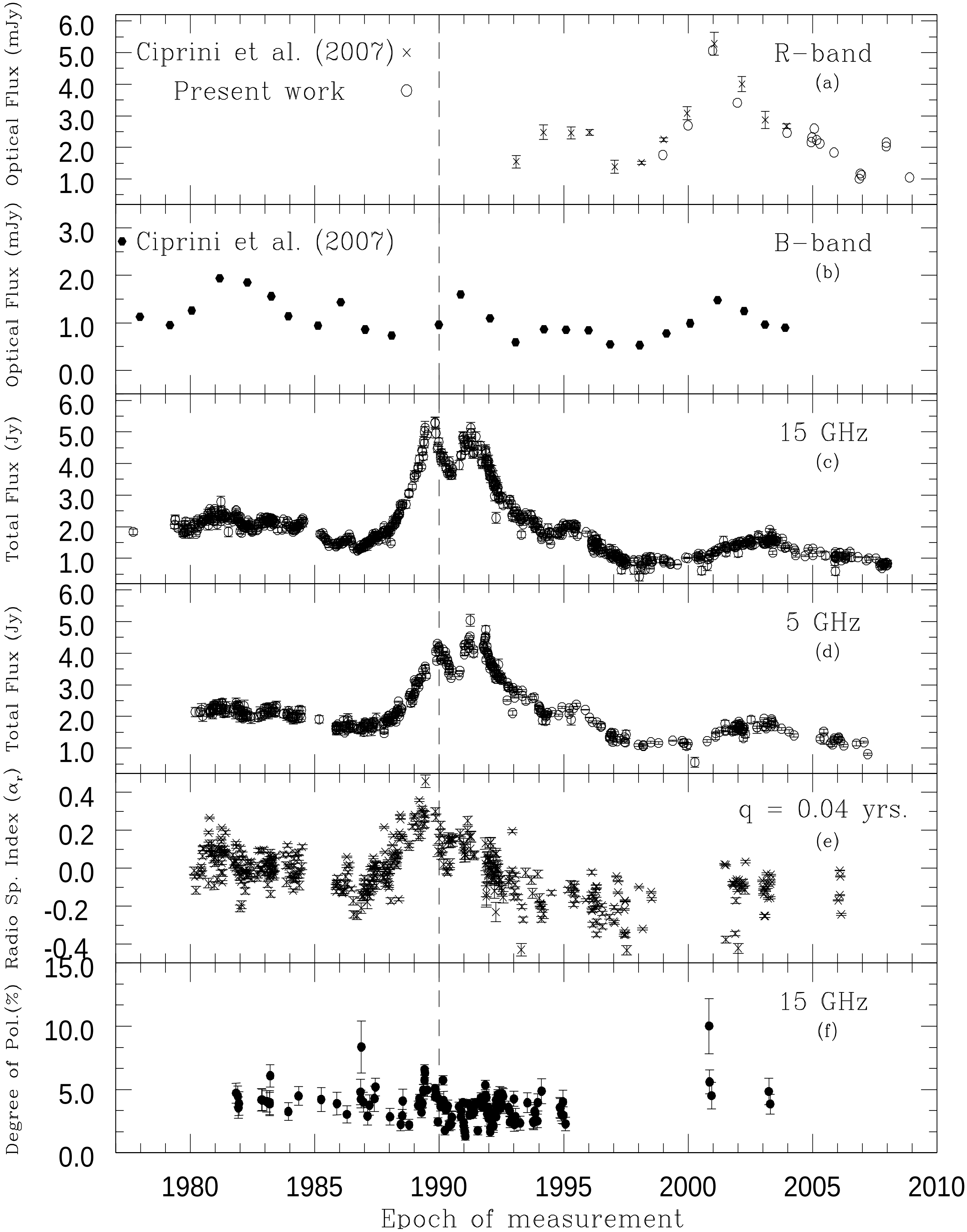

Figure 1. Light curves of PKS 0735+178 (Sect. 4); the vertical broken line marks the epoch of its historical maximum in radio brightness.

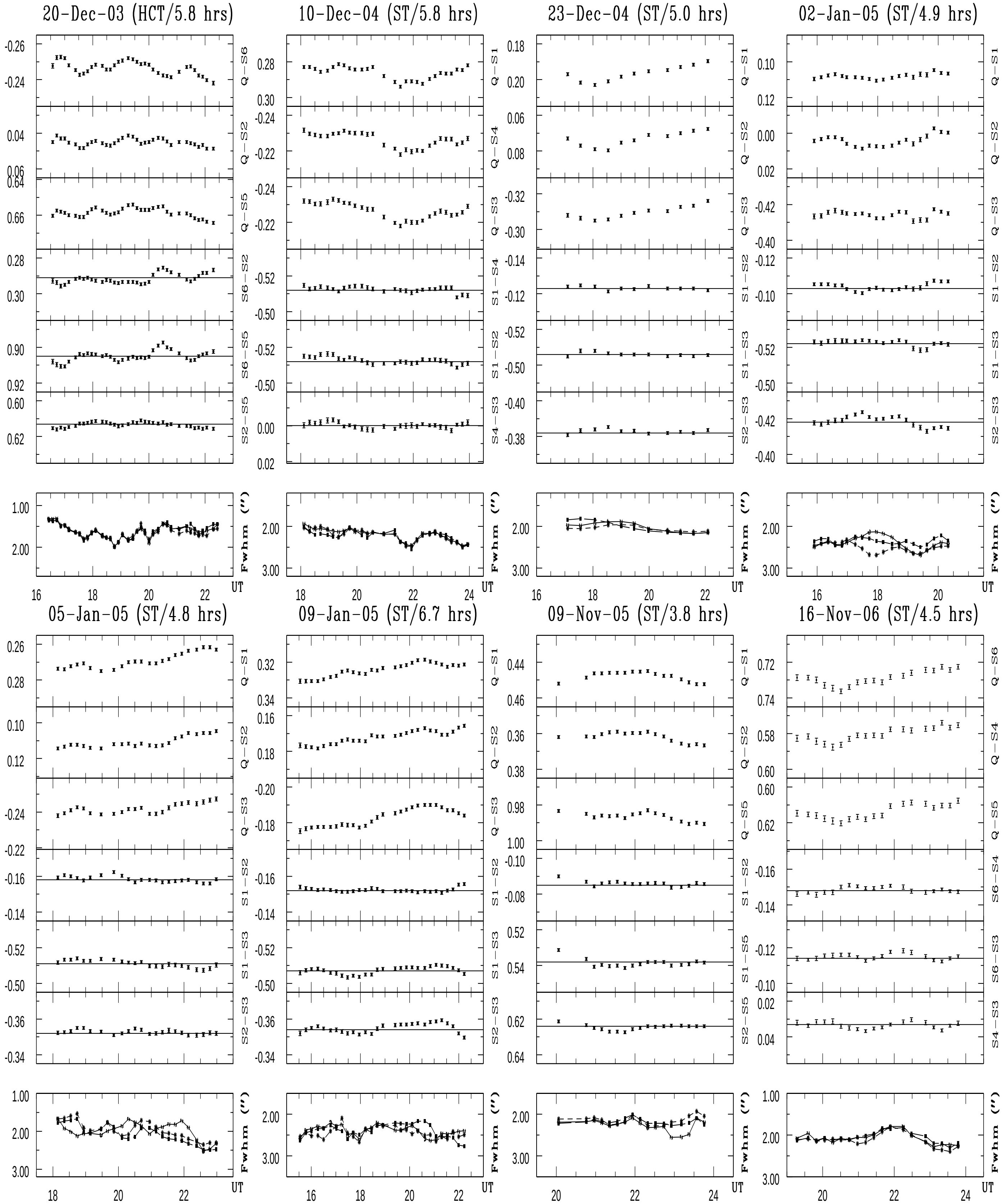

Figure 2. The intranight DLCs of PKS 0735+178. For each night the upper three panels show the DLCs of the blazar relative to three steady comparison stars while the lower three panels show the star-star DLCs. The bottom panel gives the plots of seeing variation for the night, based on three stars. For each night, the date, duration of monitoring and the telescope used are

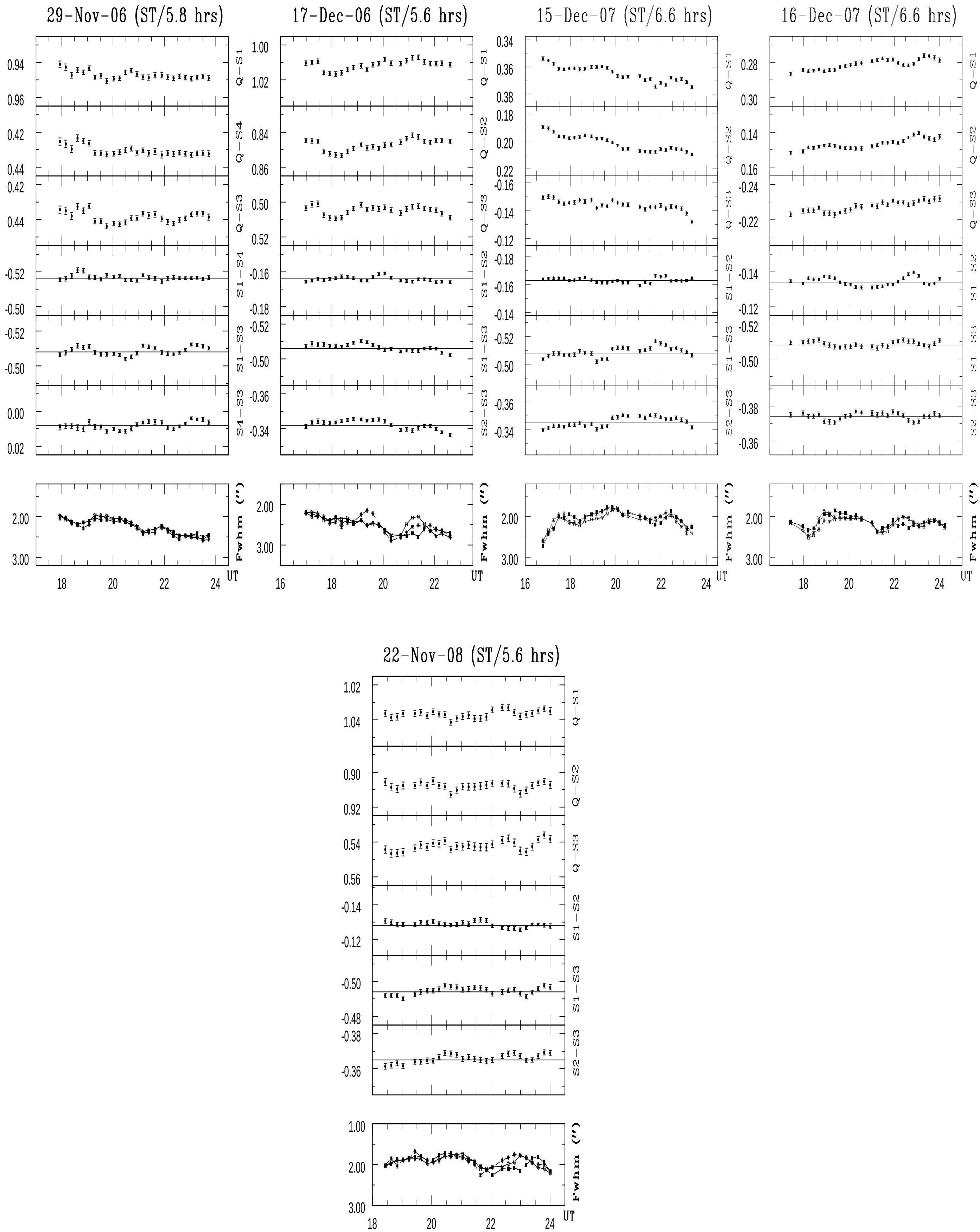

Figure 2. *continued*

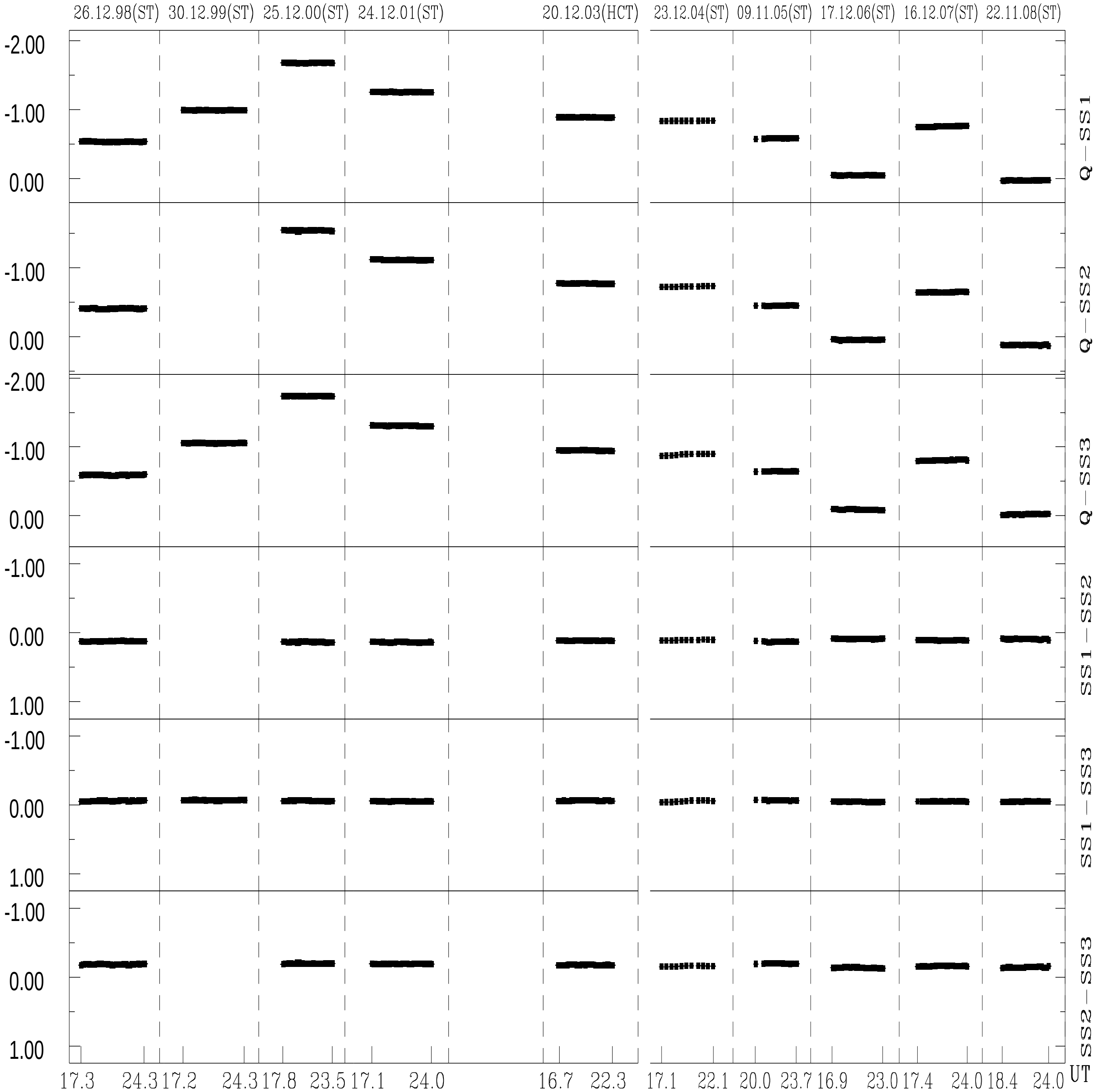

Figure 3. The long-term R-band differential light curves of PKS 0735+178, derived from from our data spanning 11 years (1998-2008). In order to maintain consistency with our already published data (Sagar et al. 2004), we have used the same three comparison stars for generating these LTOV plots. Each horizontal sedgement of the light curves represents the DLC for the night corresponding to the date mentioned at the top, along with the telescope used (shown in parentheses).

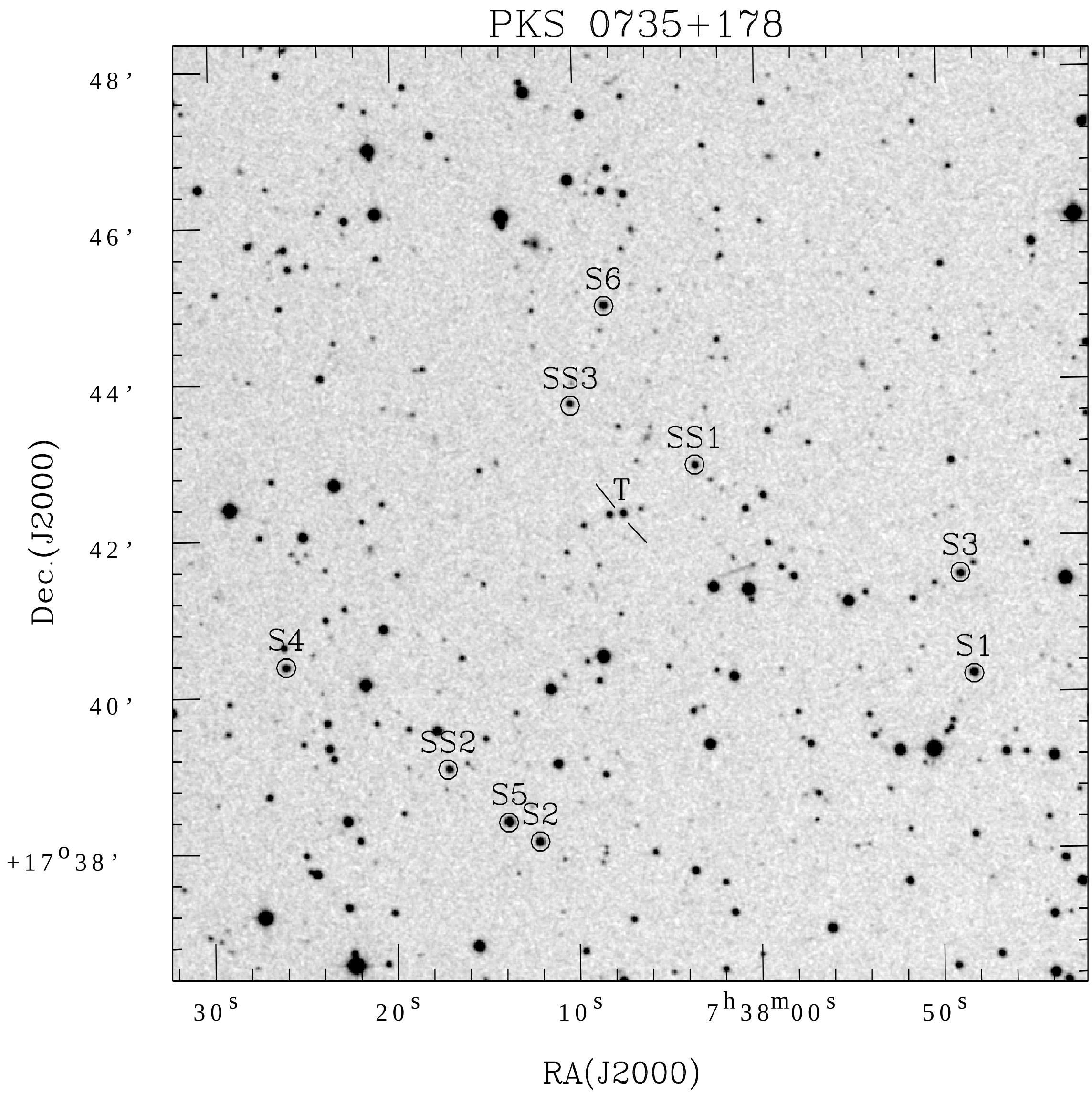

Figure 4. DSS POSS2 R-band $12' \times 12'$ field centered on PKS 0735+178 is shown. The positions of target AGN (marked with T, within double bar) and the comparison stars is shown within circles and marked with S1...S6 and SS1..SS3 notations used for making INOV & LTOV plots, respectively.