A&A 517, A63 (2010)
DOI: 10.1051/0004-6361/200913497

Astronomy & Astrophysics

Colour behaviour of the blazar PKS 0735+178 in 1994–2004 *(Research Note)*

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Received 19 October 2009 / Accepted 21 April 2010

ABSTRACT

Context. The properties of variable sources responsible for blazar activity are still under discussion. Some conclusions can be drawn from analyzing monitoring observations.
Aims. The results of multicolour monitoring observations of the blazar PKS 0735+178 are used to study the colour behaviour of the variable source responsible for the blazar activity in 1994−2004.
Methods. The method of "flux-flux" diagrams is used to find the SED of the variable source.
Results. The SED of the variable source was unchanged on timescales of years and is represented well by a power-law. High observed polarization and power-law spectrum point to the synchrotron nature of the variable source. The achromatic variability can then be explained by variations in the Doppler boosting due to ∼10°-variations in the angle between the line of sight and the velocity direction of the radiating source.
Conclusions. There is no doubt about the synchrotron nature of the variable source. The most probable reason for this variability is the change in the Doppler boosting.

Key words. BL Lacertae objects: general – BL Lacertae objects: individual: PKS 0735+178 – techniques: photometric

1. Introduction

This article is devoted to studying the colour behaviour of the blazar PKS 0735+178 in optical wavelengths. The source was optically identified from the PKS radio catalogue by Blake (1970) and classified as a BL Lac object by Carswell et al. (1974). The absence of emission lines in its spectrum does not allow any determination of its redshift z, but an absorption feature identified with Mg II line gives an estimation of $z \geq 0.424$. This object has been studied in all spectral regions from radio to γ. A good review of papers devoted to it is given by Ciprini et al. (2007, Paper I) and will not be repeated here. Let us only point out that the object is photometrically active, and its optical variability amplitude is as high as 3^{m} (Fan et al. 1997).

For clarifying the nature of the active sources responsible for blazar variability, we need to find the spectral energy distribution (SED) of these sources. But the separation of source radiation from the total observed flux, which includes the radiation of the host galaxy, accretion disk, etc., is not a simple task because the contributions of these components can only be found indirectly (if at all). In some cases, however, the relative SED of the variable source can be found from multicolour photometric monitoring data without any preliminary separation of the contribution of the components (Hagen-Thorn & Marchenko 1999). Results of such a monitoring of PKS 0735+178 are given in Paper I, and are used in this investigation.

2. Observational data and results of their analysis

The light curves of PKS 0735+178 in B, V, R, I bands given in Paper I cover the 11-year time interval 1994−2004. They are constructed using CCD-data obtained at 5 observatories with relatively small telescopes; therefore, on average, the errors of individual brightness estimations are as high as $0\overset{\mathrm{m}}{.}08$ for B, $0\overset{\mathrm{m}}{.}07$ for V, $0\overset{\mathrm{m}}{.}04$ for R, and $0\overset{\mathrm{m}}{.}06$ for I. With such high errors in magnitudes the individual estimations of colour-indexes are very unreliable. Moreover, because of relatively small flux variability on short timescales, these errors prevent colour variability investigations on less than ∼1 year timescales. Only long-term (years) colour behaviour of the source can be studied.

We used the method of colour variability analysis, described in detail in Hagen-Thorn & Marchenko (1999) and repeatedly tested in blazar investigations (for instance, Hagen-Thorn et al. 2008, 2009). The method is based on comparing quasi-simultaneous estimations of flux densities (below "fluxes") in the used spectral bands. If the photometric behaviour of the object during a given time interval is defined by a single variable source with varying flux density but unchanged SED, then in "flux-flux" diagrams (F_i vs. F_j) the points presenting simultaneous observations must lie on a straight line. With some caveats, the opposite is also true. If the points on "flux-flux" diagrams lie on straight lines, conclusion may be drawn about the constancy of the SED of the variable source responsible for the

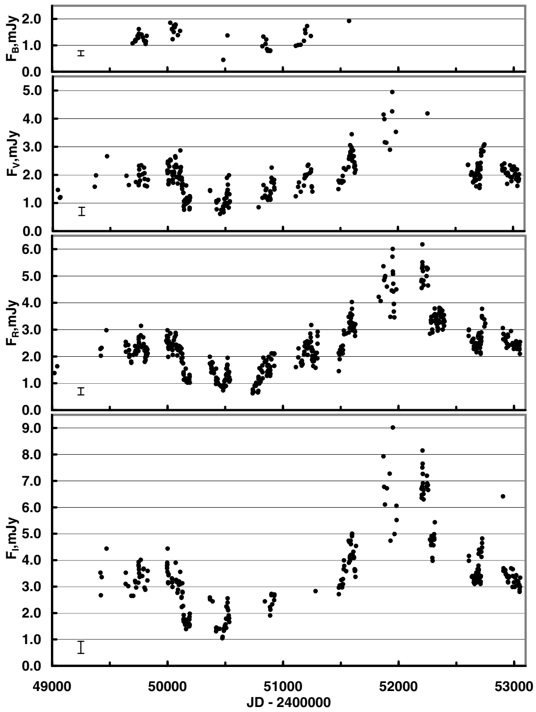

Fig. 1. The light curves after averaging within JD.

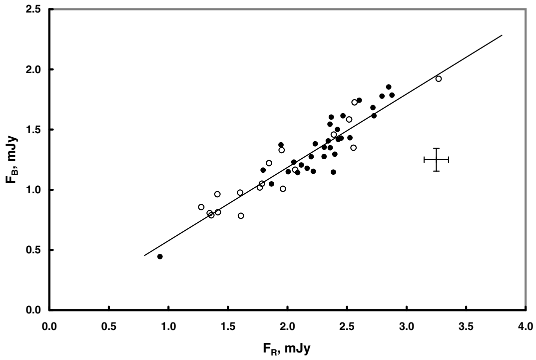

Fig. 2. Flux-flux diagram F_B vs. F_R. Cross gives the mean error at the 1σ level; the number of points = 50.

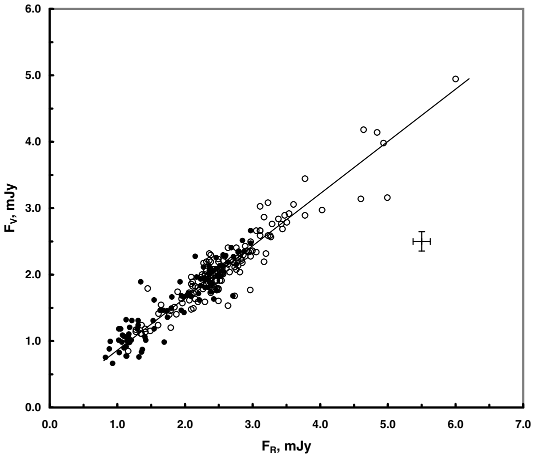

Fig. 3. Flux-flux diagram F_V vs. F_R. Cross gives the mean error at the 1σ level; the number of points = 238.

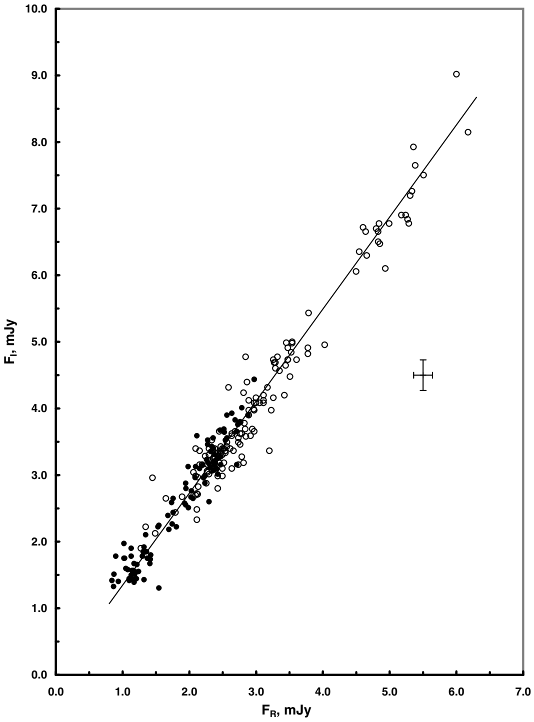

Fig. 4. Flux-flux diagram F_I vs. F_R. Cross gives the mean error at the 1σ level; the number of points = 245.

variability in the time interval considered, and the slopes of the lines are the flux ratios of the variable source in corresponding bands $(F_i/F_j)_{\rm var}$. In other words, the relative SED of the variable source has been found in the spectral range determined by these used bands. We stress that this SED is found *directly* from observational data without knowledge of the contribution of the variable component to the total observed radiation.

The magnitudes from Paper I were transformed to fluxes using the absolute calibration by Mead et al. (1990). Then, if there were several observations on some Julian Date, the mean values for fluxes in each band were calculated (thus, we ignore a possible fast variability within the night-IDV). But more often we found only one observation per night.

The obtained light curves are shown in Fig. 1, where the vertical segments give doubled mean errors. There is a trend in the light curves: before JD 2 450 700 the flux decreased on average (event 1), and after this date a flux increase is seen, which might point to the appearance of a new variable source with other colour characteristics (event 2).

The "flux-flux" diagrams are shown in Figs. 2–4. The R band, in which most observations were carried out, was chosen as the base one. In all figures, the filled circles show the data for the event 1, the open circles for the event 2. One can see that the points lie along straight lines and that there are no systematic differences between the positions of both symbol types. (This is confirmed by the data of Cols. 5 and 6 of Table 1: there are no differences at 2σ level.) Though the data for fading part in event 2 are incomplete, the behaviour on rising and fading parts of the light curve seems to be the same. The slopes of dependences F_I vs. F_R are the same (1.429 ± 0.032 and 1.397 ± 0.021). Thus, the colour characteristics of the variable component were unchanged during all eleven years. The straight lines in Figs. 2–4 (for all the data) were calculated by the orthogonal regression method.

The slopes of these lines and their errors are given in Table 1 in the fourth column. (In previous columns the spectral

Table 1. The results of determination of the relative SED of the variable source.

Band 1	log ν 2	$r_{iR} \pm 1\sigma$ 3	$(F_i/F_R)^{\mathrm{obs}} \pm 1\sigma$ 4	$(F_i/F_R)^{\mathrm{obs},1} \pm 1\sigma$ 5	$(F_i/F_R)^{\mathrm{obs},2} \pm 1\sigma$ 6	$(F_i/F_R)^{\mathrm{corr}} \pm 1\sigma$ 7	$\log(F_i/F_R)^{\mathrm{corr}} \pm \sigma$ 8
B	14.833	0.926 ± 0.054	0.610 ± 0.036	0.729 ± 0.057	0.538 ± 0.051	0.643 ± 0.038	−0.192 ± 0.025
V	14.736	0.941 ± 0.022	0.786 ± 0.017	0.816 ± 0.031	0.802 ± 0.024	0.802 ± 0.017	−0.096 ± 0.009
I	14.574	0.975 ± 0.014	1.382 ± 0.014	1.437 ± 0.031	1.411 ± 0.022	1.350 ± 0.014	0.130 ± 0.005

Notes. (3) – Correlation coefficient between fluxes and its error, all values of r are near 1. (4–6) – Observed SEDs of the variable source (4 – all the data, 5 – event 1, 6 – event 2). (7) – Corrected SED of the variable source (all the data). (8) – The same in logarithmic scale.

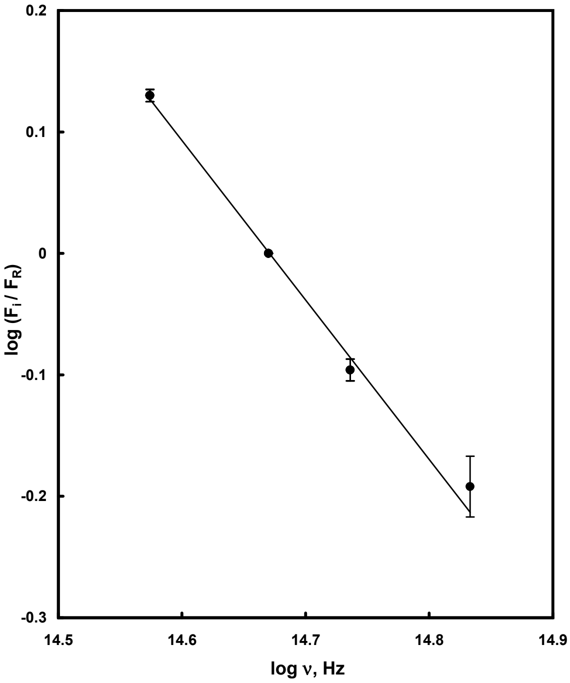

Fig. 5. The spectrum of the variable source.

band, corresponding logarithm of the frequency, and correlation coefficient between fluxes with its error are given.) The data in the fourth column give the *observed* relative SED of the variable component responsible for the long-term variability.

This SED must be corrected for reddening due to light absorption in our Galaxy. This may be done by multiplying the data of Col. 4 by the factor $C_{iR} = 10^{0.4(A_i - A_R)}$ (A_i according to the NED). The seventh column gives the relative SED of the variable source corrected for Galactic absorption. In the eighth column this is shown on a logarithmic scale.

Results of determining the relative SED of the variable source are shown in Fig. 5 (for R band log $\nu = 14.670$). It is seen that the points lie along a straight line quite well, showing a power-law spectrum ($F_\nu \sim \nu^\alpha$). The straight line is calculated by the least-squares method with the errors taken into account. The result gives the spectral index $\alpha = -1.31 \pm 0.07$.

3. Discussion

Power-law spectrum and observed high polarization (≈20%, e.g. Mead et al. 1990) point to the synchrotron nature of the variable source. Paper I is devoted, in principle, to searching for periodic components in the light curve of PKS 0735+178; however, it contains a part devoted to analysing of colour variability (see Fig. 5 in Paper I). The authors used another method for the analysis than here. They suggest that all the observed flux is radiated by the variable component and find spectral indexes for individual observations suggesting a power-law spectrum. The mean value of the spectral index $\alpha = -1.25 \pm 0.15$ found by them agree with our value. They affirm that light variability is achromatic on the time-scales of years (we agree with this), but in individual events colour variability possibly exist. We stress that our observational data do not permit us to state anything about colour variability on the shorter time-scales (days/weeks). This is evident if we compare the scatter of the points relative to the straight lines in Figs. 2–4 with the 1σ errors shown in the figures by crosses. The whole scatter of the points relative to the straight lines may be attributed to accidental errors, and the flux variability can be explained if the variable source does not change its SED.

The colour characteristics of the variable source may be different on different time intervals. Thus, from the PKS 0735+178 observations in 1982−84 published by Sitko et al. (1985) and Smith et al. (1987), a variable source with spectral index $\alpha = -1.50 \pm 0.03$ was found by Hagen-Thorn et al. (1990) when applying the same method as used here. A variable source with $\alpha = -1.65$ can be found from the data published by Mead et al. (1990) for observations carried out in 1988. This means that, at different time intervals, the energy distribution in the assembly of relativistic electrons responsible for synchrotron radiation may be different.

The constancy of the spectral shape of the variable component excludes all variability mechanisms, resulting in a change in SED (for instance, fading because of synchrotron losses). For synchrotron sources, achromatic variability is best explained by the change in the relativistic boosting of the flux due to variation in the Doppler-factor δ ($F \sim \delta^{3-\alpha}$), which is caused by the change in the angle between the line of sight and velocity direction of the moving source θ.

The movement of the superluminal component in the radio jet of PKS 0735+178 gives a Lorentz-factor Γ between 2 and 4 (Agudo et al. 2006). If we accept $\Gamma = 3$, then we get $\beta = 0.9428$ for the velocity of the source. The ratio of fluxes in maximum and minimum brightness (see Fig. 1) is $F_{\max}/F_{\min} = 6$. For $\alpha = -1.31$, the corresponding ratio of the Doppler-factors will be $\delta_{\max}/\delta_{\min} = 1.52$. Keeping in mind that $\delta_{\max}/\delta_{\min} = (1-\beta\cos\theta_{\min})/(1-\beta\cos\theta_{\max})$, we suggest $\theta_{\max} = 0$ and find a lower limit for the angle at minimum $\theta_{\min} > 14°$ and $\delta_{\min} < 3.84$. For a more realistic value $\theta_{\max} = 10°$, it will be $\theta_{\min} \sim 19°$ and $\delta_{\min} \sim 3.07$. Evidently, these estimations are valid only for time interval 1994−2004.

4. Conclusions

Thus, the results of the colour behaviour investigation of blazar PKS 0735+178 based on the 11-year (1994−2004) four-colour (B, V, R, I) photometric monitoring can be summarised as follows.

Long-term (years) variability in optical wavelengths is caused by the flux variations in the source with unchanged relative SED. This SED is represented well by a power-law spectrum, which is a property of a homogenous synchrotron source ($F_\nu \sim \nu^{-1.31\pm0.07}$). The synchrotron nature of the variable source is confirmed by the high polarization observed in PKS 0735+178.

Most probably, the achromatic variability stems from a change in the Doppler-factor within limits of 3 to 5, which is caused by about a 10° change between the line of sight and velocity direction of the moving source.

Acknowledgements. This work was supported by RFBR grant No. 09-02-00092. V.A. and E.I.H.-Th. thank Tuorla Observatory for hospitality.

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