Prominent outburst of the blazar CTA 102 in 2012

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Abstract

After few years of quiescence, the blazar CTA 102 underwent a large outburst in the fall of 2012. The flare has been traced from gamma-rays to near-infrared, including *Fermi* and *Swift* data and polarimetric data from several observatories. An intensive GASP-WEBT collaboration campaign in optical and NIR bands, using also previously unpublished archival data, allowed to compare this outburst with the previous activity period of this blazar in early 2000th. We found remarkable similarity between optical and gamma-ray behavior of CTA 102 during the outburst, without any time lag between the two light curves, indicating co-spatiality of the optical- and gamma-radiating regions. A strong harder-when-brighter spectral dependance is seen both in gamma-rays and optical. Polarimetric behavior of CTA 102 during the outburst conforms with the shock-in-jet interpretation.

1. Introduction

The blazar CTA 102 (4C +11.69, 2FGL J2232.4+1143, z=1.037) is a well-known quasar-type object. Like other blazars it is believed to be an active galactic nucleus where the jet is oriented close to our line of sight, which causes a high relativistic beaming of the jet's emission and a violent variability at all wavelengths. CTA 102 was first identified as a quasar in [1] and belongs to the OVV (optically violently variable) [2] as well as to the HPQ (high polarized quasars) subclasses [3].

On a long-term scale the blazar shows a rather moderate variability in optical bands. In [4] it was reported on the modest swings around the average $B=17.^m7$ during 14 yr range (about 65 observations between 1973 and 1987). An overall amplitude $\Delta R=0.^m88$ was observed by [5] in 1994-1997. However, occasional and sharp flares appear to be typical for CTA 102. Variations as high as $\Delta B=1.^m07$ in 2 days [4], $\Delta V=1.^m13$ in 3 days [6] were observed in 1978 and 1996 correspondingly. Previously reported historical maximum for the object $R\approx 14.^m5$ was reached on Oct. 4, 2004 during a short-term event accompanied by a prominent intranight variability [7]. After that and until 2012 only modest variability is seen in the light curve of this blazar (see Fig.1).

CTA 102 is known as a gamma-ray emitter since it was discovered during the early CGRO (EGRET) mission at the level $(2.4\pm0.5)\times10^{-7}$ ph cm^{-2} s^{-1} (E>100 MeV) [8]. It was also detected in the 10-30 MeV energy range by COMPTEL onboard of the CGRO [9]. Since the blazar usually stays in a quiescent state the average gamma-ray flux is rather low $(2.9\pm0.2)\times10^{-9}$ ph cm^{-2} s^{-1} (1<E<100 GeV) according to 2FGL [10]. Therefore an accurate relative timing of flux variations in gamma-ray and optical bands is only possible during large outbursts. This kind of cross-correlation analysis for several other blazars has recently shown that gamma-ray and optical flares are usually coincident and associated with a passage of a new knot through a 43-GHz radiocore [11,12]. Similar events may serve as a crucial test for models localising the gamma-ray emission in blazars (e.g., [13]).

Here we analyse the brightest outburst of CTA 102 up to date in the optical and gamma-ray bands [14].

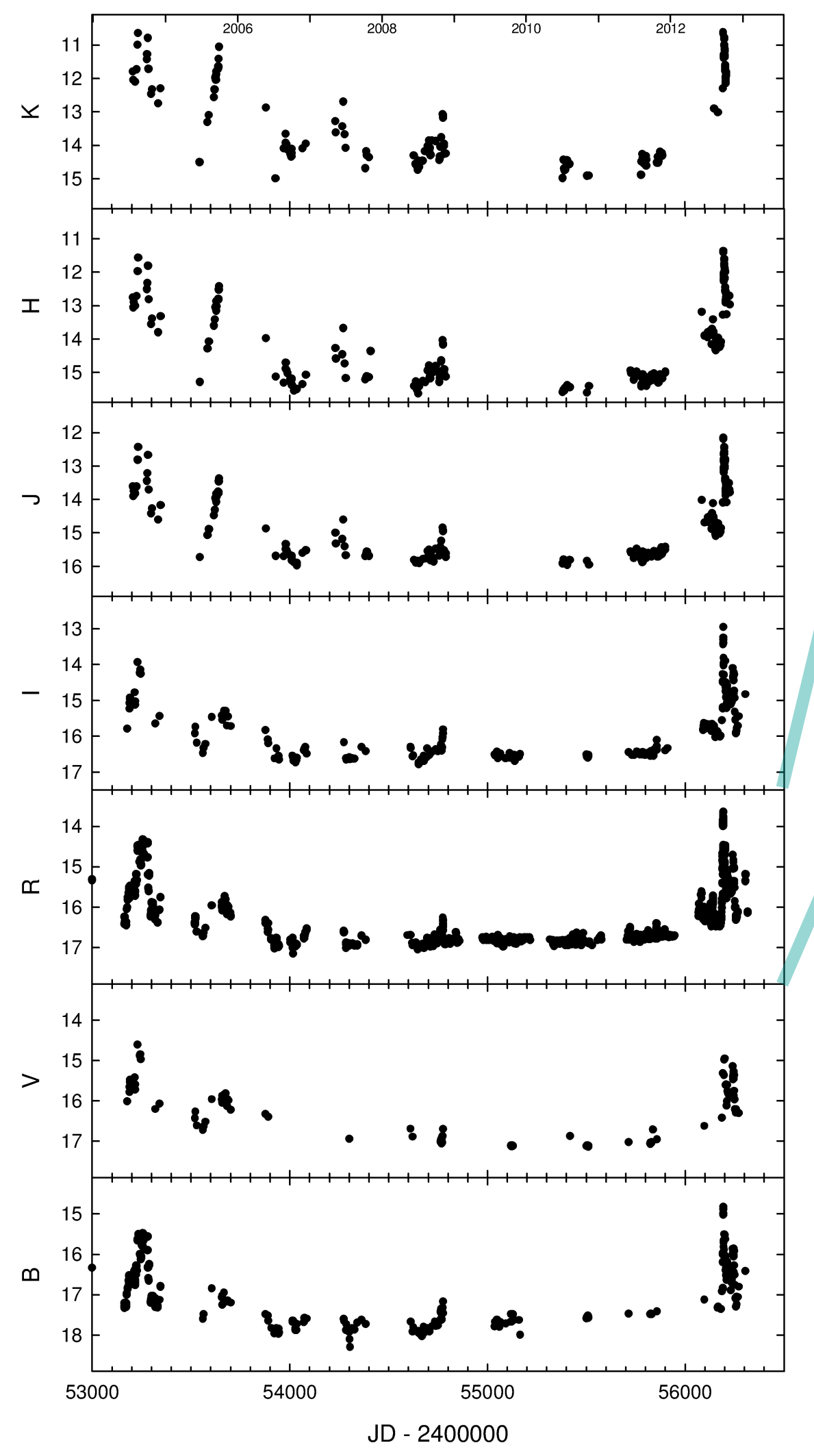

Figure 1. Optical and near-infrared light curves of CTA 102 for the time interval 2004–2013.

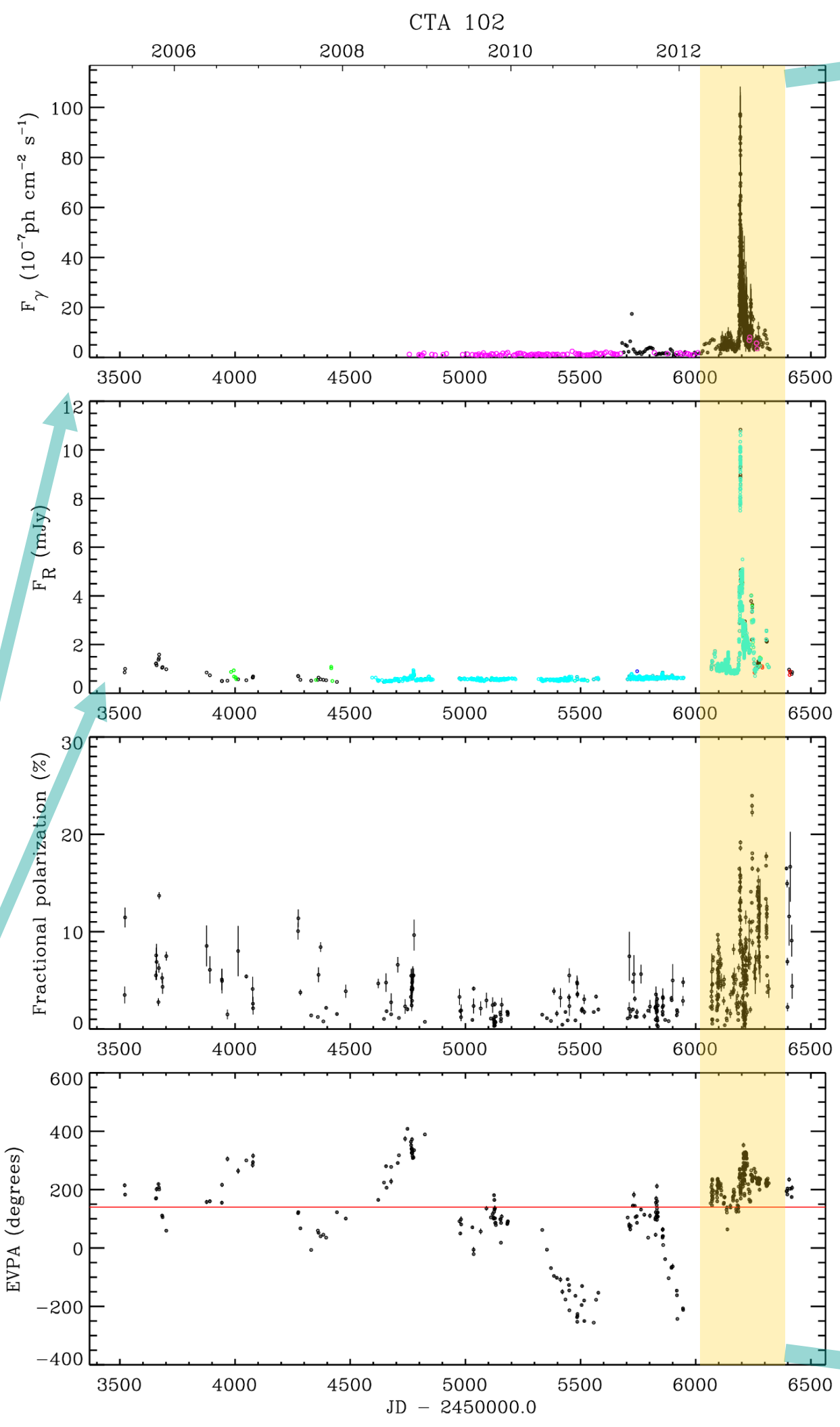

Figure 2. From top to bottom: γ-ray and optical flux evolution, optical fractional polarization and positional angle of CTA 102 for the time interval 2004–2013.

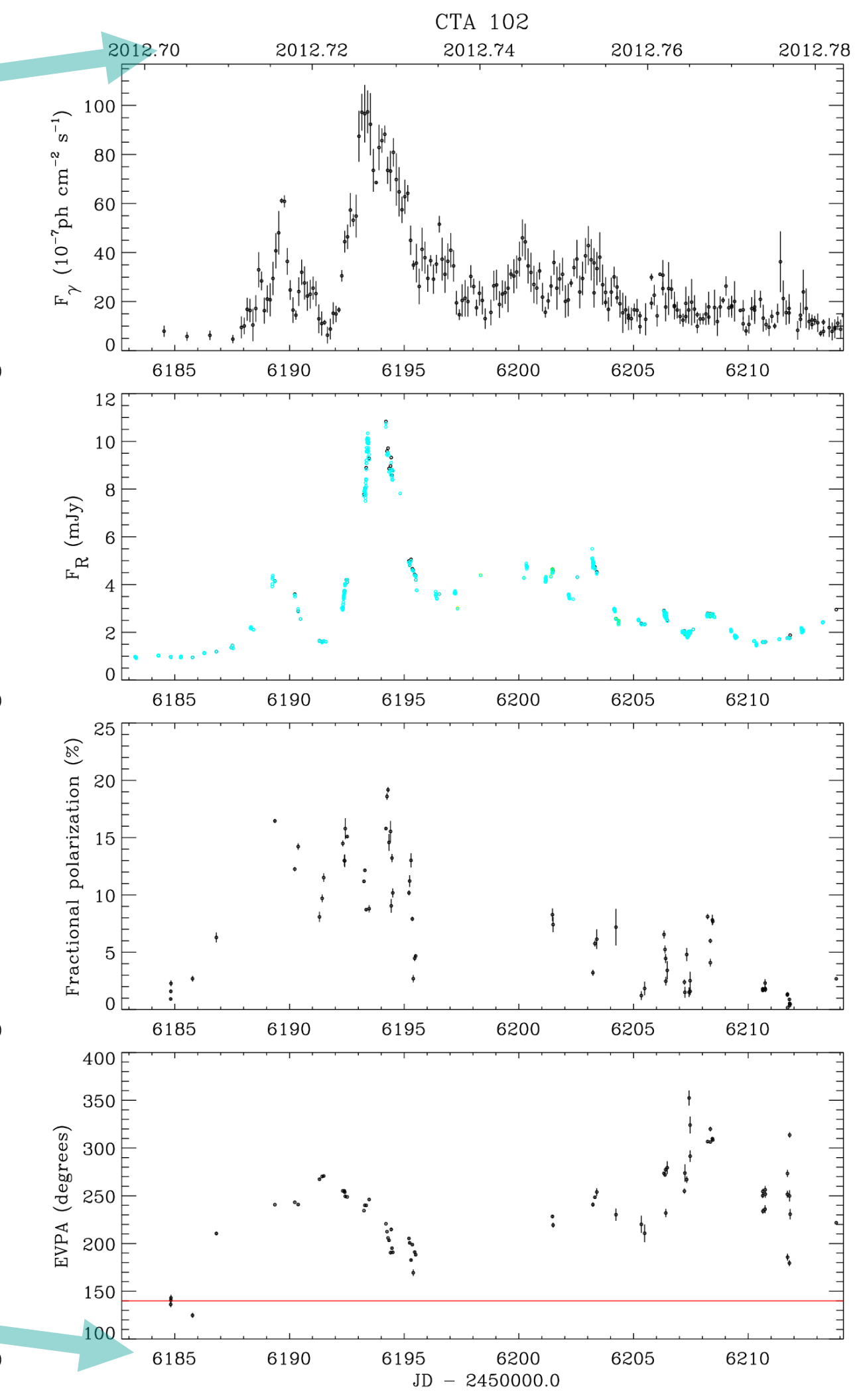

Figure 3. Blowup of Fig. 2 for 2012 September-October flare.

2. Observations and data reduction

Optical and near-infrared photometry The optical and near-IR light curves of CTA 102 for the 2004-2012 time interval are shown in Fig.1. The GASP-WEBT observations in 2008-2012 were performed in R band in the following observatories: Belogradchik, Calar Alto, Campo Imperatore, Crimean, Lowell (Perkins), Lulin, Mount Maidanak, New Mexico Skies, Roque (Liverpool Telescope), Rozhen, Sabadell, Skinakas, St. Petersburg, Teide (IAC80), and Tijarafe. The V and R-band light curves are complemented by data taken at the Steward Observatory in the framework of the monitoring program in support of the *Fermi* observations. BVI photometric data are from St. Petersburg and Lowell observatories. We also use B and R Mt. Maidanak data referring to 2004 outburst.

Optical polarimetry We use observations collected in St. Petersburg University (Crimea and St. Petersburg), Lowell (Perkins), Steward and Calar Alto observatories. Instrumental polarization was found via stars located near the object under the assumption that their radiation is unpolarized. The Galactic latitude of CTA 102 is -38° and $A_V = 0.^m16$, so that interstellar polarization (ISP) in this direction is less than 0.6%. To correct for the ISP, the mean relative Stokes parameters of nearby stars were subtracted from the relative Stokes parameters of the object. This accounts for the instrumental polarization as well. Figure 2 presents the flux and polarization behavior of CTA 102 for 2005-2012. We supplement this plot with a panel showing the gamma-ray light curve from *Fermi* LAT in order to show that the most prominent gamma-ray activity ever recorded for this source was observed during the September-October 2012 optical outburst. In Fig. 3 we show a blowup of the most exciting time interval of 2012 outburst. From visual inspection of these figures it is immediately seen that during all the time interval covered by *Fermi* observations, until 2012 season, CTA 102 remained silent both in gamma-rays and in optical; the degree of polarization was mostly ≤10%, while the positional angle showed marked ordered variations in the range [-200°, 400°]. We solved the ±180° ambiguity adding/subtracting 180° each time that the subsequent value of EVPA is >90° less/more then the preceding one. The onset of the activity in the 2012 season was accompanied with a violent increase of optical polarization activity. The degree of polarization exceeded 20% during some dates, while the positional angle showed variations in the range of 150° - 300°

Gamma-ray Observations We analyze the *Fermi* LAT data for CTA 102 with variable binning, from 1-week to 1 day, depending on the brightness of the object, as well as with a 6-hour shift, during the huge gamma-ray outburst of 2012 September-October, when the flux from the source was higher than 2×10^{-6} ph cm^{-2} s^{-1}. This prevents missing any possible short-lived events, to make the correlation analysis more robust, and to avoid the dependence of the results on the start of the time bins. In spite of high gamma-ray flux, we had to increase binning during *Fermi* LAT ToO pointing observations for S3 0218+35 that have been performed between 2012 September 24 and 30 (JD 2456195-201). We use the standard *Fermi* analysis software package Science Tools `v9r27p1`, with the instrument response function `P7SOURCE_V6`, the Galactic diffuse emission model `gal_2yearp7v6_v0`, and the isotropic background model `iso_p7v6source`. The background models include all sources from the 2FGL within 15° The spectrum of CTA 102 is modelled as a power-law with photon index selected to be a free parameter. We calculate the discrete correlation function (DCF) [15] of the optical and gamma-ray flux variations of CTA 102 during 2012. The results are given in Fig.4. It clearly demonstrates that there is no time delay between the variations in two energy bands, within the accuracy of the DCF method.

Swift observations The UVOT observations were performed in the optical *v*, *b*, and u bands, as well as in the UV filters *uvw1*, *uvm2*, and *uvw2* [16]. We reduced the data with the HEAsoft package version 6.10, with the 20101130 release of the *Swift*/UVOTA CALDB. Multiple exposures in the same filter at the same epoch were summed with `uvotimsum`, and then aperture photometry was performed with the task `uvotsource`. We used Swift calibrations according to [16].

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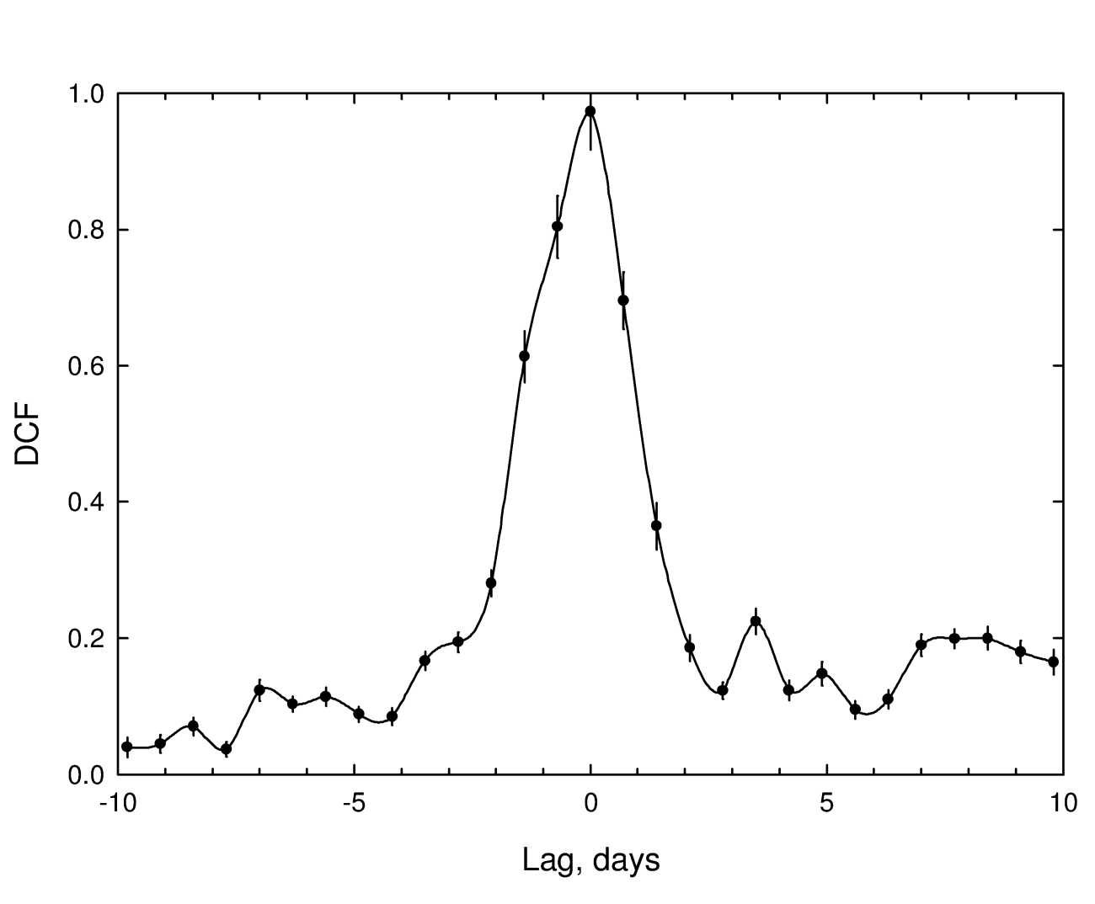

Figure 4. DCF between optical and γ-ray light curves of CTA 102. The lack of delay convincingly demonstrates co-spatiality of active regions.

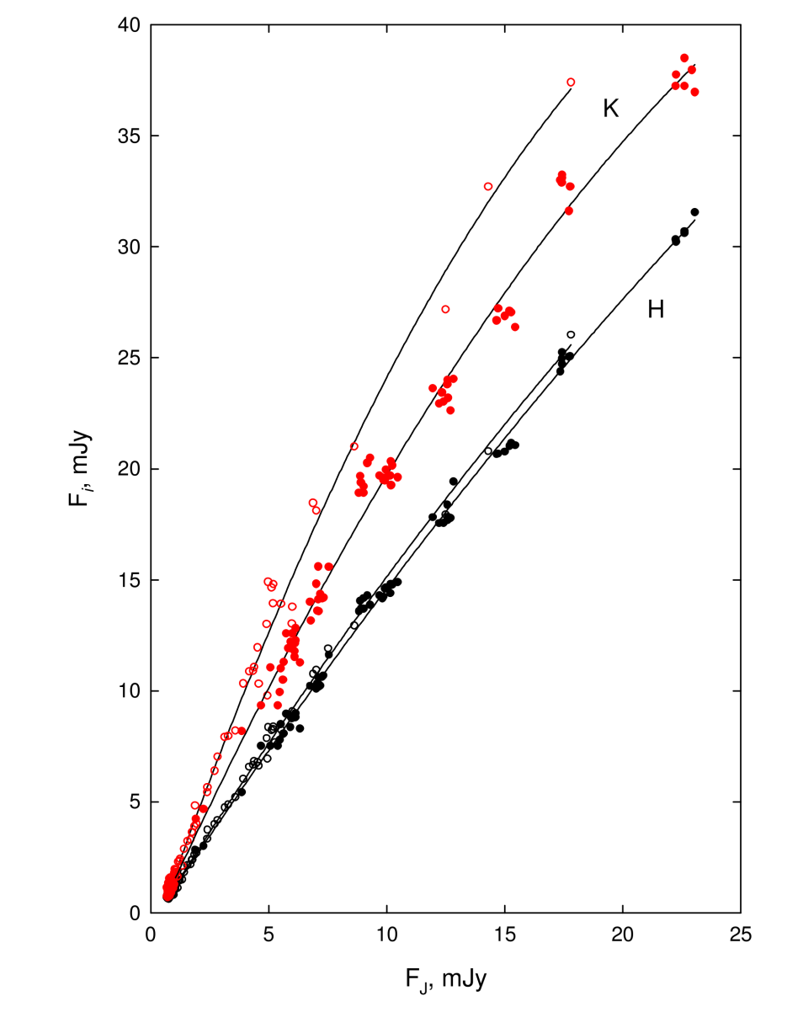

Figure 5. Two-flux dependencies in near-infrared region. Filled symbols refer to the time interval 2008–2012, open symbols – to the 2004 outburst.

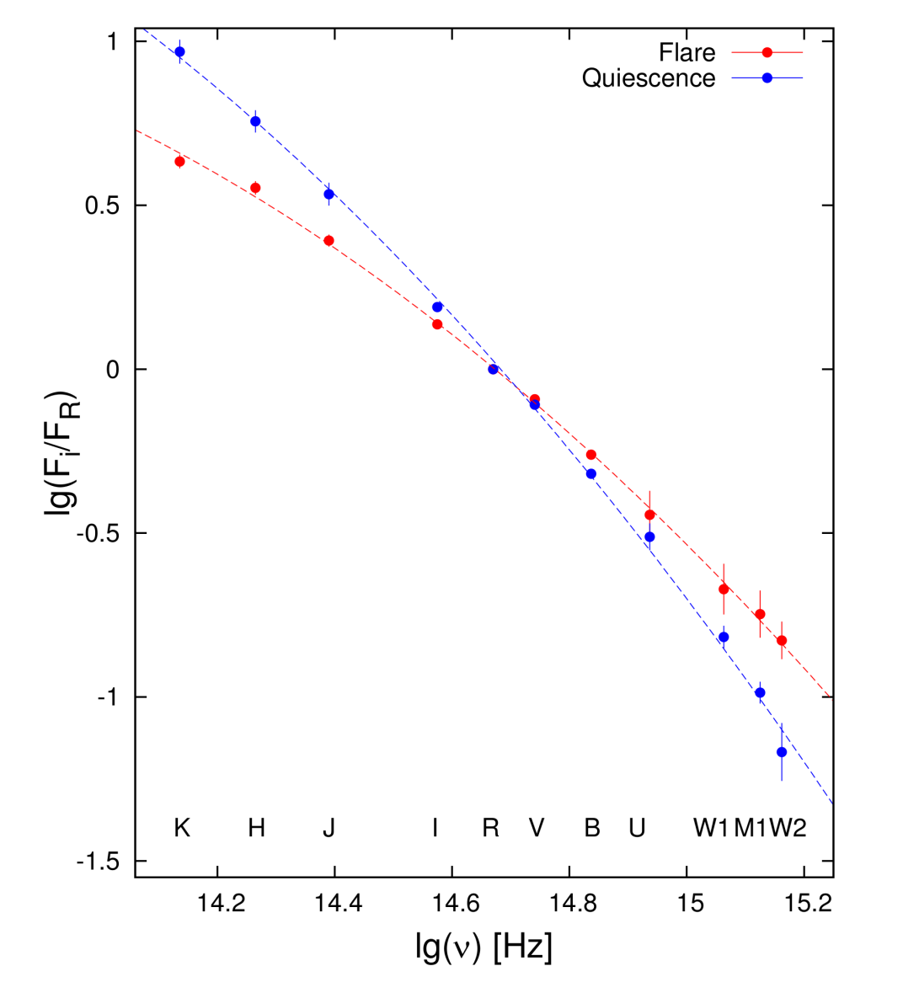

Figure 6. Relative SEDs of *variable* source in CTA 102 radiation during quiescence (blue) and 2012 flare (red) from UV to NIR.

3. Discussion

Color evolution

The question whether blazar's radiation is reddening or blueing when it brightens is a topic of numerous papers. It is commonly agreed that the relative contribution of Big Blue Bump (BBB), Doppler-boosted synchrotron radiation of the jet and shock wave(s) are different during quiescence and in outburst and that leads to differing SEDs. The situation is even more complicated e.g. in case of CTA 102, when non-negligible emission in broad emission lines distorts broad-band photometry (Mg II λ 2800 line is redshifted to λ 5600). A straightforward way to segregate the contribution of the component of radiation that is variable on the shortest time scales (presumably, synchrotron radiation) is suggested in numerous papers of Hagen-Thorn and co-workers; see also [17,18] and Hagen-Thorn's poster on this Workshop. The method is based on plotting of (quasi)simultaneous flux densities in different color bands and construction of relative SED based on the slopes of the sets of two-flux dependencies obtained that way.

An example of such approach is given in Fig. 5, where the flux densities in H and K bands are plotted against J band flux density. This Figure demonstrates that low- and high-flux behavior either reflect variability of different sources of radiation (e.g. jet in low state and shock - in high state) or, if the same source is responsible for all variability pattern, its parameters substantially change depending on the source's brightness. More of that, the slopes obtained during 2012 season substantially differ from those of 2004 outburst (open symbols in the same Fig. 5). In the Fig. 6 we plot relative SEDs of variable source in CTA 102 for quiescence and 2012 outburst from *Swift* UV to NIR bands, that show marked hardening of the SED during high state, together with substantial curvature of the spectrum. It is tempting to suppose, as suggested in [18] for the case of BL Lac, that this spectral hardening is explained by the change of the viewing angle of the emitting zone, and corresponding shift of the position of synchrotron peak due to Doppler boosting. Otherwise we may suppose that the populations of emitting electrons are very different in quiescence and outburst.

The simultaneous spectral hardening in the gamma-ray region during outburst is also demonstrated in Fig. 7. Notice that in this Figure we plot total observed flux densities, as opposed to Fig. 6.

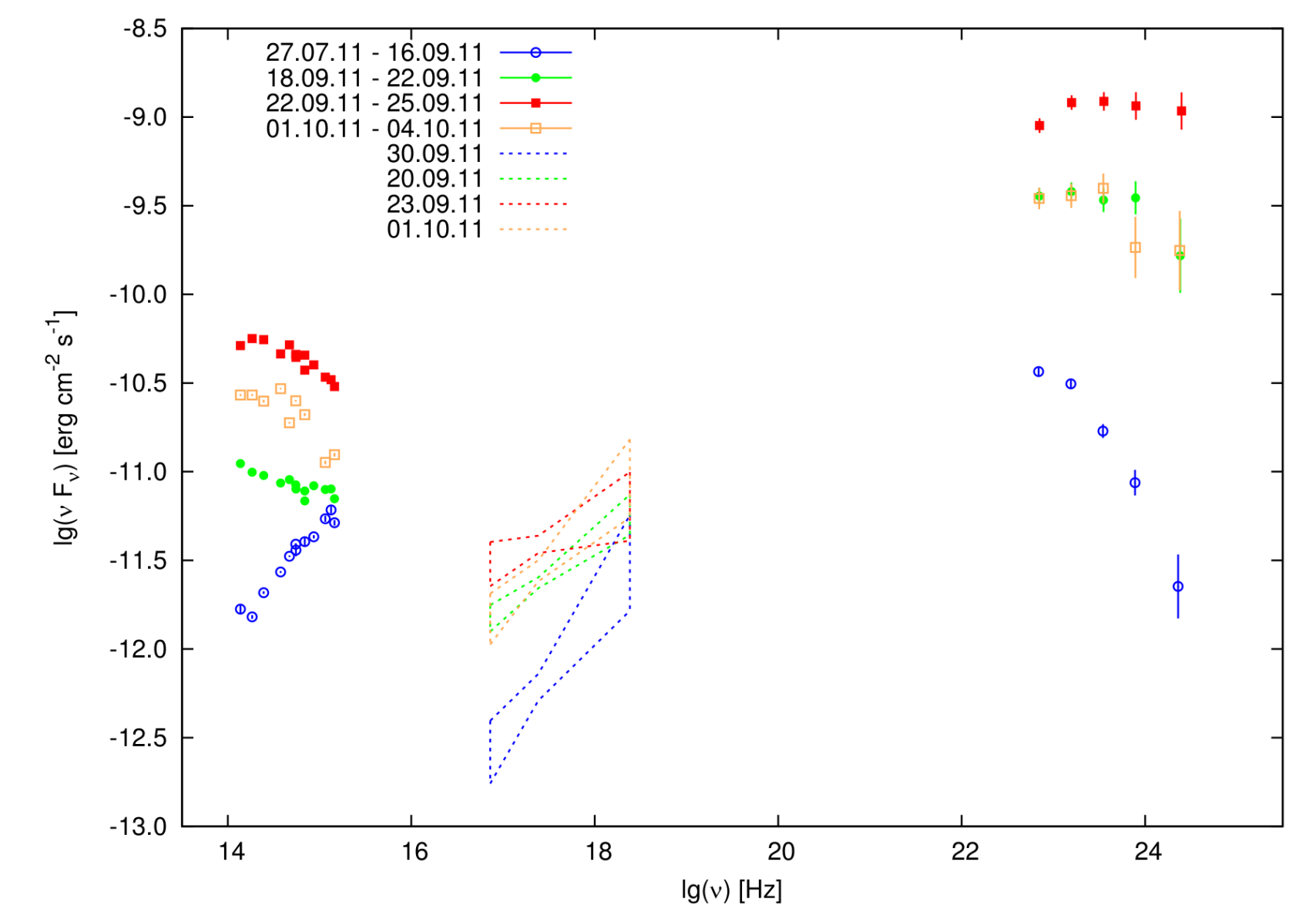

Figure 7. (Quasi)simultaneous SEDs of CTA 102 radiation from γ-rays to NIR.

Polarimetric behavior

Figure 8 shows the distribution of normalized and absolute Stokes parameters of CTA 102 both for quiescence and different stages of the 2012 activity interval. We notice a marked drift of the centrum of gravity of *qu* points during and after the outburst as compared to their pre-outburst position. This may reflect the change of orientation of the jet itself. We also found four episodes of clockwise rotation (loops) both in *q-u* and *Q-U* plots. All of them correspond to local increases of brightness (upper panel of the same Figure).

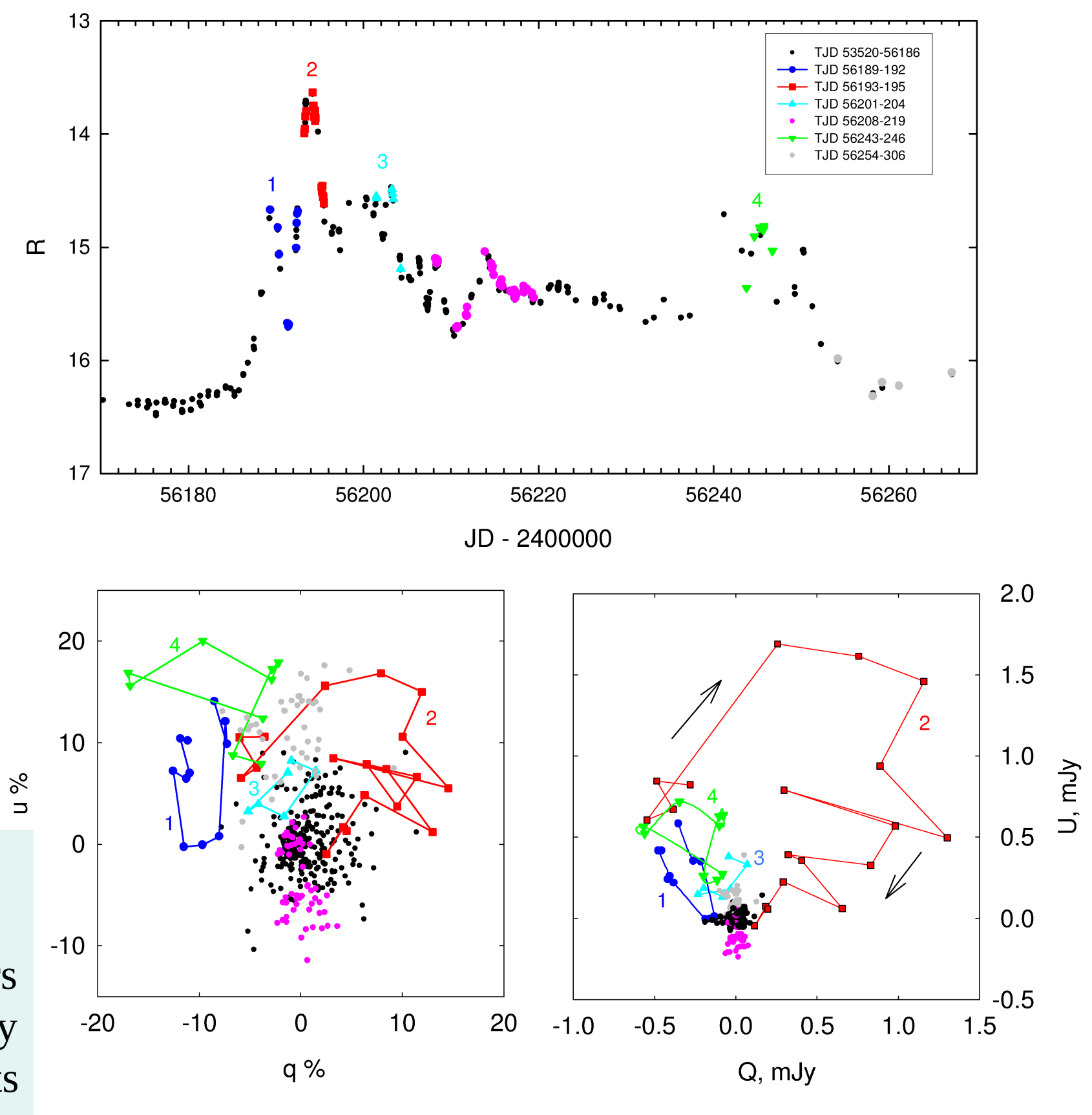

Figure 8. Lower left: normalized *q* and *u* Stokes parameters of CTA 102 radiation; lower right: the same for absolute Stokes parameters. Upper panel: *R* band light curve with the same color encoding as in lower panels.

As in the case of S5 0716+71 [19], we use a model of a relativistic shock moving in the helical jet to explain these rotations. It is a challenging task since most probably we observe several separate events: spiral movement of a shock during main flare of JD 2456188-6205, with three consecutive clockwise loops; a flare without rotation, but with marked downward drift on q-u plane (JD 2456210-6220); a new prominent flare (JD 2456243-6248), again with a clockwise loop; and following it on the descending branch of the light curve, upward movement in the q-u plane. We notice that our finding of clockwise rotation of polarization vector is supported by the detection of negative circular polarization in the 15 GHz radio emission of CTA 102 [20]. Thus it is a persistent feature of this blazar.

4. Conclusions

Finally, we conclude that 2012 exceptional outburst of CTA 102 allowed to trace strong correlated changes of spectral energy distribution of this blazar from gamma-rays to near-infrared, the source beeing harder when brighter; polarimetric observations reveal loops in Stokes parameters space caused by helical structure of the jet.

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