Multiwavelength Observations of 6 BL Lac Objects in 2008-2012

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Abstract

We present results of 4 years of multifrequency observations of 6 BLLac objects (3C 66A,S5 0716+71 ,PKS 0735+17,S4 0954+68,W Com and OT 081) carried out with the Fermi Large Area Telescope (LAT) at gamma-rays , with different ground based telescopes in photometric mode at optical wavelengths, and with the Very Long Baseline Array (VLBA) at 43 GHz. We have analyzed total intensity images of the blazars obtained with the VLBA to study the kinematic evolution of the pc-scale jets of the sources. For all sources we have compared flux variations in the VLBI core and bright superluminal knots with gamma-ray and optical light curves.The majority of gamma-ray flares coincide with the appearance of a new superluminal knot as well as with a flare in the optical band and in the millimeter-wave core. These results support the conclusion that many gamma-ray and optical flares in blazars originate in the vicinity of the millimeter-wave core or even downstream the jet.

1. Introduction

Blazars display high variability at different timescales over a broad range of frequencies. Their extreme properties are thought to be owing to their relativistic jets pointing toward us. Although blazars comprise only a few percents of the overall AGN population, they represent the most numerous class of objects identified with gamma-ray sources. The origin of this high-energy radiation is still not clear, although according to the radio-interferometer observation the gamma-ray bright blazars have the most relativistic jets [1,2]. There are a number of studies that reveal a connection between the gamma-ray emission and jet properties (e.g. [3,4,5]).

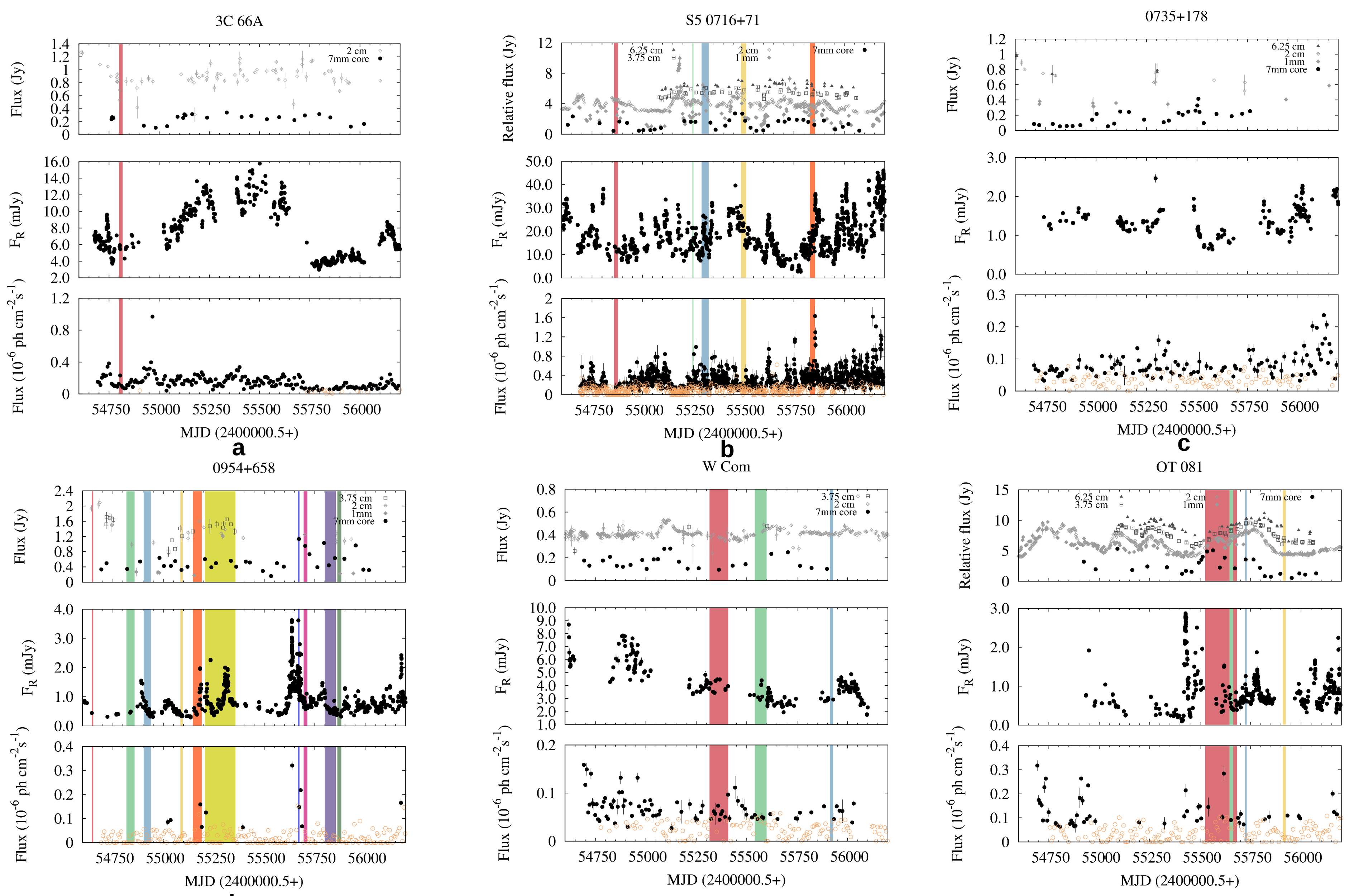

Figure 1: From top to bottom: the light curves at radio wavelengths (1mm, 7mm, and 2cm), the R-band optical light curves, and the Fermi LAT gamma-ray light curves (orange circles correspond to upper limits) of the sources. Multicolor horizontal lines correspond to times of knot ejection.

2. Observations and data reduction

We obtain optical (R-band) flux densities from photometric observations at the 0.4 m telescope of St.Petersburg State U. (LX200) and 0.7 m telescope of the Crimean Astrophysical Observatory (AZT-8). The data analysis for these telescopes is described in [6]. We also use R-band data carried out with the Perkins Telescope (BU group)*, Liverpool Telescope, Calar Alto Telesopes*, and Steward Observatory* .

We derive 0.1-200 GeV gamma-ray flux densities by analysing data from the Large Area Telescope (LAT) of the Fermi Gamma-ray Space Telescope with the standard software [7]. We have constructed gamma-ray light curves with binning from 1 to 7 days (depending on the source's brightness), with a detection criterion that the maximum-likelihood test statistic (TS) should exceed 10.0.

We use total intensity radio images derived by BU group at 43 GHz with VLBA*. We have modelled the images in terms of a small number of components with circular Gaussian brightness distributions. The core is a stationary feature located at one of the ends of the portion of the jet that is visible at 43 GHz. Identification of components in the jet across the epochs is based on analysis of their flux, position angle, distance from the core, and size. We have computed kinematic parameters of the knots (proper motion, velocity, and acceleration) by fitting the positions of a component over epochs by different polynomials of order from 1 to 4 in the same manner as described in [8]. Also we use data of UMRAO, OVRO, and SMA to construct radio band light curves.

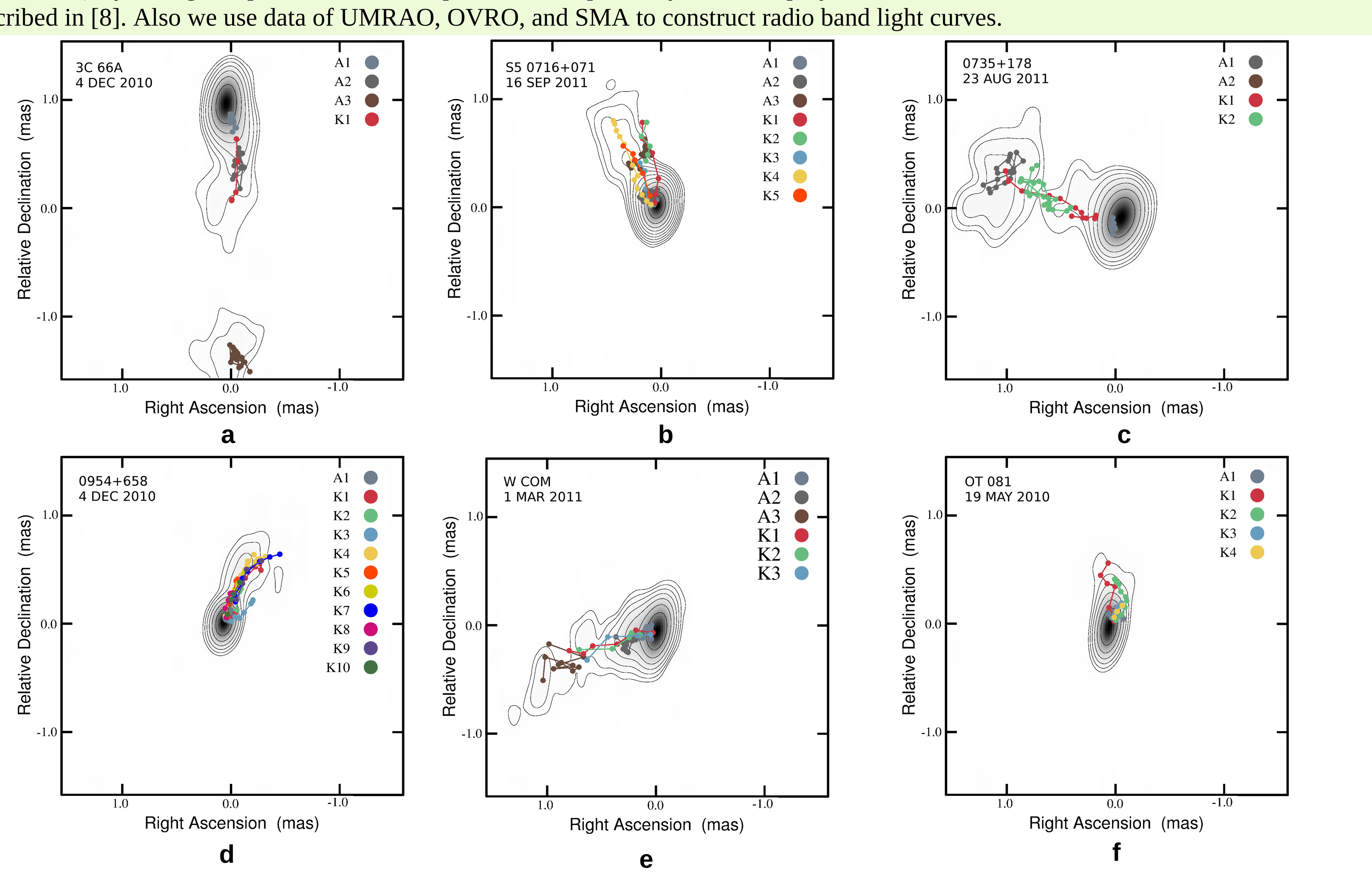

Figure 2: VLBA-maps of the sources overlayed with trajectories of the knots.

Knot	β_{app} c	$<\Theta>$ $degrees$	$\dot{\mu}_{\vert\vert}$ mas/yr^2	$\dot{\mu}_{\perp}$ mas/yr^2	T_{eject} MJD	γ-flare T_{max} MJD	F_{max}/F_{mean}
3C 66A							
K1	30.7 ± 1.7	-171.5 ± 5.1	-	-	54809 ± 9	54805.5	1.6
S5 0716+71							
K1	26.1 ± 0.5	11 ± 9.6	0.71 ± 0.14	1.53 ± 0.02	54869 ± 10	-	-
K2	20 ± 0.15	10.5 ± 2.9	-	-	55250 ± 2	55265.5	2.9
K3	22.8 ± 0.4	41 ± 20	-	-	55310 ± 17	55308.5	1.6
K4	16.1 ± 0.9	39.5 ± 14.3	0.23 ± 0.02	-0.24 ± 0.04	55500 ± 13	55512.5	1.5
K5	21.4 ± 2.1	27.8 ± 4.1	-	-	55842 ± 12	55856.5	3.8
0735+178							
K1	20.1 ± 2.9	78.1 ± 7.4	1.2 ± 0.01	-0.06 ± 0.01	-	-	-
K2	4.1 ± 0.2	73 ± 6.7	0.02 ± 0.01	-0.1 ± 0.01	-	-	-
S4 0954+68							
K1	13.4 ± 0.3	-28.9 ± 5.5	-0.71 ± 0.03	-0.4 ± 0.02	54649 ± 3.5	-	-
K2	11.7 ± 1.7	-26 ± 6.3	-	-	54838 ± 20	-	-
K3	7.5 ± 0.5	-52.9 ± 5.2	-0.28 ± 0.03	0.35 ± 0.03	54920 ± 17	-	-
K4	6.9 ± 0.4	-20 ± 6.7	-0.39 ± 0.01	-0.18 ± 0.01	55090 ± 6	-	-
K5	13 ± 1.4	-13.7 ± 0.8	-	-	55169 ± 21	55183.5	1.2
K6	13.6 ± 3.8	-17.8 ± 1.1	-	-	55281 ± 74	55211.5	0.92
K7	19.3 ± 0.2	-25.4 ± 6.4	-0.95 ± 0.04	-0.88 ± 0.03	55671 ± 3	55638.5	2.4
K8	17.2 ± 1.4	-8.4 ± 4.4	-	-	55704 ± 9	55680.5	1.6
K9	26.6 ± 1.6	-24.1 ± 3.1	-	-	55827 ± 27	-	-
K10	20.2 ± 0.9	-14.6 ± 2.6	-	-	55872 ± 9	-	-
W Com							
K1	4.7 ± 0.5	95.3 ± 10.6	-	-	55362 ± 46	55442.5	1.6
K2	4.5 ± 0.8	98 ± 6.7	-	-	55570 ± 29	55442.5	1.6
K3	5.9 ± 0.4	99.2 ± 6.6	-	-	55920 ± 8	-	-
OT 081							
K1	17 ± 0.6	-6.7 ± 15.7	0.51 ± 0.18	-0.26 ± 0.02	55604 ± 79	55617.5	2.2
K2	8.1 ± 0.1	-25 ± 15	-0.38 ± 0.03	0.53 ± 0.01	55654 ± 9	55617.5	2.2
K3	7.5 ± 0.2	-22.6 ± 2.9	-	-	55727 ± 4	-	-
K4	14.4 ± 1.0	-26.3 ± 2.7	-	-	55917 ± 7	-	-

Table 1: Parameters of the knots

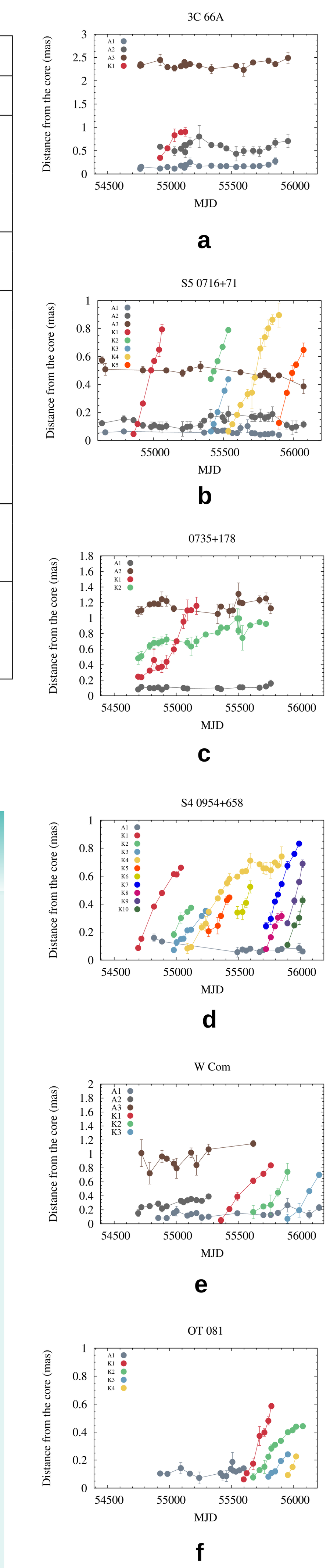

Figure 3: Position of jet features with respect to the core as a function of time.

3. Results and Discussion

Figs.1(a-f) present (from top to bottom) the light curves at radio wavelengths (1 mm, 7 mm, 2cm, 3.75 cm and 6.25 cm), the R-band optical light curves, and the Fermi Large Area Telescope gamma-ray light curves (orange circles correspond to upper limits) of 6 blazars during the period from August 2008 to August 2012. Figs.2(e-f) show the VLBA images of the sources at 43 GHz. We have examined VLBA images of the sources for both variability of the core and the appearance of superluminal knots ejected from 2008 to 2012. Tab.1 presents the apparent speed of moving knots, acceleration, mean position angle with respect to the core, time of the separation from the core, and the existence of a gamma-ray flare.

We have detected both moving and stationary components in all 6 objects (see Fig.3). According to [3] «stationary hot spots» are a common characteristic of compact jets, with the majority of such features located within a range of projected distances of 1-3 pc from the core. Sources 3C 66A, S5 0716+71 , PKS 0735+17, S4 0954+68, W Com , and OT 081 revealed 1, 5, 2, 10, 3, and 4 moving knots, respectively. All sources are bright enough to be detected routinely at gamma-ray energies, except S4 0954+68, which is marginally detected with 7-day binning.

All sources demonstrate variability from radio to optical wavebands. The source S5 0716+71 exhibits the highest gamma-ray activity during 2008-2012, however all the other sources show substantial variability in gamma-ray band. The gamma-ray activity coincides with an increase of the total intensity in the core at 43 GHz (7 mm) and the appearance of superluminal knots in the jet.

The blazar 3C 66A: The light curve shows increasing gamma-ray flux of the object during MJD 54700-55750 (Fig.1a). The source demonstrates a high level of the optical flux and an increase of the radio flux during this period. A new superluminal knot K1 passed through the mm-wave core after the second gamma-ray flare (MJD 54805).

The blazar S5 0716+71: Persistent activity is apparent across the electromagnetic spectrum (Fig.1b). We have identified 5 superluminal knots K1-K5 (Fig.3b), out of which 3 components were emerged in the jet during the high optical and gamma-ray state. As we have reported in [9] knot K5 appeared at MJD~ 55850, which coincides within 1σ uncertainty with the time of the highest peak in the gamma-ray light curve. This event is accompanied by a rotation of the position angle of optical polarization (EVPA) of 180˚. In addition, we have found a change in the jet direction from ~11˚ (in 2008-2010, knots K1, and K2) to ~36˚ (in late 2010-2012, knots K3-K5).

The blazar PKS 0735+17: We have detected 2 moving knots in PKS 0735+17 (Fig.3c). The source did not exhibit a high activity in either the gamma-ray or optical band, nor did we detect any new knots ejected during the period of observations.

The blazar S4 0954+68: The light curve in Fig.1d shows a high activity of the source in the optical band beginning at MJD~54900 with a number of strong flares. We have identified 10 superluminal knots (Fig.3d), out of which 9 (K2-K10) components were emerged into the jet during the high optical state. Although the gamma-ray flux fell below the detection limit during most of the period of our observations, there are a number of positive detections of gamma-ray events during the strong optical flares that were contemporaneous with the passages of knots through the core. The ejection of knots K7, and K8 coincides with the major flare in the R-band light curve and detections in the gamma-ray light curve. As we have reported in [10] the appearance of the knot K7 was accompanied by a significant rotation, ~ 300˚, of the optical EVPA. All components have nearly the same position angle ~-20˚, except the component K3, which has Θ ~-53˚.

The blazar W Com: In W Com we observe 3 moving knots (Fig.3e). A new superluminal knot K1 passed through the mm-wave core before the gamma-ray flare (MJD~55450) and knot K2 emerged from the core after the flare.

The blazar OT 081: The light curve in Fig.1f shows a high activity of the source in the optical and radio bands. Although the source is usually quite faint at gamma-ray energies, there are a number of gamma-ray flares that appear to be associated with flares at optical and radio wavelengths. We observe 4 moving knots, whose appearance in the jet is accompanied by an increase of flux of the core (Fig.1f). The trajectory of knot K2 is significantly curved (Fig.2f). The time of the passage of knots K1, K2, and K3 through the mm-wave core coincides with the gamma-ray and optical events.

4. Conclusions

Over the period from August 2008 to August 2012, we detected superluminal motion in all 6 objects with apparent speeds ranging from 4 c to 30 c. We find that high levels of the gamma-ray activity in 5 out of the 6 blazars studied coincide with the production of a new superluminal knot and/or a flare in the millimeter-wave core, as well as flares at optical and radio wavelengths. For a number of components we have not detected gamma-ray flares near the ejection time; however, in the majority of these cases, optical R-band flares are seen at that time. These results support the conclusions that gamma-ray and optical flares in blazars are cospatial, and that many of these flares are located in the vicinity or downstream of the mm-wave VLBI core. However, the data do not exclude that some events can be produced closer to the central engine.

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Calar Alto Telesopes(MAPCAT) website: http://www.iaa.es/~iagudo/research/MAPCAT/MAPCAT.html