A multi-wavelength view of VHE gamma-ray flares from Mrk 421 and Mrk 501 observed by ARGO-YBJ experiment

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Abstract: As the most active blazars, Mrk 421 and Mrk 501 are excellent candidates for the study of the physical processes within the jets of active galactic nuclei. Since August 2008, these sources have been monitored daily by the ARGO-YBJ experiment at γ-ray energies above 0.3 TeV, by Fermi-LAT at 0.1-300 GeV γ-ray energies, by BAT/Swift at 15-50 keV hard X-rays, by ASM/RXTE, MAXI and XRT/Swift at 0.3-20 keV soft X-rays. Here we report a multi-wavelength view of the large flares from Mrk 421 and Mrk 501 during the period from August 2008 to January 2013, which were simultaneously observed by these detectors. The emission spectra of the low and high energy bumps are well measured. The evolution of the spectra during different flares is presented.

Keywords: Mrk 421, Mrk 501, gamma ray observation, AGN, ARGO-YBJ

1 Introduction

Blazars, including BL Lac objects and flat-spectrum radio quasars (FSRQ), are the most extreme class of active galactic nuclei (AGNs). Most of the identified extragalactic γ-ray sources belong to this category. Their emission is believed to be dominated by non-thermal and strongly Doppler-boosted radiation from a relativistic jet which is aligned along our line of sight. Their spectral energy distributions (SEDs) are characterized by two distinct bumps. The lower energy component is usually interpreted to be caused by the synchrotron radiation from relativistic electrons (and positrons) within the jet. The origin of the higher energy component is under debate. The leptonic models attribute the γ-ray emission to the inverse Compton scattering of the synchrotron (synchrotron self-Compton, SSC) or external photons (external Compton, EC) by the same population of relativistic electrons. The hadronic models attribute the γ-ray emission to proton-initiated cascades and/or proton-synchrotron emission in a magnetic field-dominated jet.

According to most of the multi-wavelength observation results, the X-rays and very high energy (VHE) γ-rays are tightly correlated during the flaring periods. A very rapid γ-ray variability is observed. Recently, a long-term continuous monitoring of Mrk 421 has been performed based on the ARGO-YBJ experiment and satellite-borne X-ray detectors [1]. According to this investigation, a good long-term correlation in both time and spectrum is evident. All the observational features are taken as challenges to models based on hadronic processes but as evidences for leptonic models. According to recent cumulative evidence [2], SSC mechanism seems to dominate the emission from BL Lac objects while the EC component becomes important for FSRQ. The lack of strong emission lines in the radiation from BL Lac objects is also taken as one of the evidences for a minor role of ambient photons (e.g., [3]), and hence the SSC model is favored for BL Lac objects. Therefore, BL Lac objects are less affected by the circumambient background radiation and are taken as the ideal targets for the study of the physical processes within the jets of AGNs. However, even in the framework of the SSC model, the fundamental question of the origin of the flux and spectral variability, observed on timescales from minutes to tens of years, is still open.

To understand the variability of emission and the underlying acceleration and radiation mechanisms in jets, continuous multi-wavelength observations, particularly in X-ray and γ-ray bands, are crucial especially if over a very long term. The broad band energy spectra could provide constraints on the model parameters. The Cherenkov telescopes can not monitor constantly AGNs because of their limited duty cycle and narrow field of view (FOV). The wide-FOV EAS arrays, operated with high duty cycle, are more suitable for monitoring. A review about EAS array observations of AGNs can be found in [4]. Working at energies above 300 GeV, ARGO-YBJ extends the multi-wavelength survey carried out by the satellite-borne X-ray detectors Swift, RXTE, MAXI and the GeV γ-ray detector Fermi-LAT. In particular, the SED is covered without any gap from 100 MeV to 10 TeV. All the measurements would set strong constraints on the emission model of AGNs.

Mrk 421 (z=0.031) and Mrk 501 (z = 0.034) are classified as BL Lac objects. They are the two brightest blazars known and are detected with high significance by the ARGO-YBJ experiment. Mrk 421 is a very active blazar with major outbursts about once every two years in both X-rays and γ-rays. Mrk 501 also entered into a active phase in October 2011 and this activity lasted up to about June 2012. Therefore, they are excellent candidates for the study of the physical processes within the jets of AGNs. In this paper, we report on the multi-wavelength view of the large flares from Mrk 421 and Mrk 501 during the period from August 2008 to January 2013.

2 Observations and data analysis

The ARGO-YBJ experiment [5] is a full coverage extensive air shower detector with RPCs at Yangbajing (4300 m a.s.l., Tibet, China). The full detector has been in stable data taking from 2007 November to January 2013. The trigger rate is ~3.5 kHz with a dead time of 4% and the average duty cycle is higher than 86%. The data analysis is
Fig. 1: Five day-averaged light curve of Mrk 421 measured by BAT/Swift at 15–50 keV. The vertical dashed lines indicate the periods of the six flares analyzed in this paper. All the errors are statistical at 1 σ.

Fig. 2: SED of Mrk 421 derived during the period of six flares (blue points) and the long-term low state (red points). The magenta arrows indicate the 95% confidence level flux upper limits set by Fermi-LAT and ARGO-YBJ. The grey points indicate the SED obtained by [12].

Table 1: SED results for Mrk 421, the unit for integral flux F is (ph cm$^{-2}$ s$^{-1}$)

<table>
<thead>
<tr>
<th>MJD</th>
<th>$F_{\text{2–10keV}}$ ($\times 10^{-2}$)</th>
<th>$\alpha$</th>
<th>$F_{\text{&gt;0.1GeV}}$ ($\times 10^{-8}$)</th>
<th>$\alpha$</th>
<th>$F_{\text{&gt;1TeV}}$ ($\times 10^{-11}$)</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flare 1</td>
<td>55121–55153</td>
<td>12.7±0.2</td>
<td>19.7±2.0</td>
<td>1.93±0.03</td>
<td>2.7±0.7</td>
<td>1.76±0.05</td>
</tr>
<tr>
<td>Flare 2</td>
<td>55242–55245</td>
<td>29.4±1.1</td>
<td>33.8±0.5</td>
<td>1.86±0.09</td>
<td>1.52±0.01</td>
<td>1.70±0.02</td>
</tr>
<tr>
<td>Flare 3</td>
<td>55245–55272</td>
<td>15.2±0.1</td>
<td>17.4±0.2</td>
<td>1.93±0.02</td>
<td>1.70±0.02</td>
<td>1.70±0.02</td>
</tr>
<tr>
<td>Flare 4</td>
<td>55475–55503</td>
<td>9.7±0.4</td>
<td>22.3±2.1</td>
<td>2.01±0.11</td>
<td>1.74±0.05</td>
<td>1.74±0.05</td>
</tr>
<tr>
<td>Flare 5</td>
<td>55811–55822</td>
<td>12.3±0.2</td>
<td>22.1±0.1</td>
<td>1.94±0.04</td>
<td>1.74±0.01</td>
<td>1.77±0.02</td>
</tr>
<tr>
<td>Flare 6</td>
<td>56117–56187</td>
<td>7.6±0.2</td>
<td>58.4±1.9</td>
<td>2.39±0.07</td>
<td>1.77±0.02</td>
<td>1.77±0.02</td>
</tr>
<tr>
<td>Low state</td>
<td>55516–55801</td>
<td>1.63±0.05</td>
<td>18.0±0.5</td>
<td>2.39±0.11</td>
<td>1.75±0.03</td>
<td>1.75±0.03</td>
</tr>
<tr>
<td>Low state</td>
<td>55831–56106</td>
<td>1.63±0.05</td>
<td>2.39±0.11</td>
<td>1.75±0.03</td>
<td>0.42±0.16</td>
<td>2.30±0.43</td>
</tr>
</tbody>
</table>

Carried out as described in [1]. The so-called “direct integral method” [2] is applied to estimate the number of cosmic ray background events.

Fermi-LAT is a pair-construction telescope, with a FOV over 2 sr, active in the 100 MeV–300 GeV energy range with an unprecedented sensitivity [7]. Fermi has begun to monitor the whole sky daily since August 2008. In this work, we use the LAT data from a region of radius 15° centered on Mrk 421 and Mrk 501. The analysis is performed using the ScienceTools (Version v9r31p1) provided by the Fermi collaboration [3]. The data are processed following the standard recommendations for the binned method.

BAT/Swift is a highly sensitive large FOV instrument. It is a coded aperture mask imaging telescope with FOV 1.4 sr. With a rather long exposure by orbiting the Earth every 1.5 hours, the data from BAT/Swift can also produce

a sensitive hard X-ray all-sky survey. The data publicly available are used in this work. For Mrk 421 and Mrk 501 the daily flux at energies 15-50 keV started in February 2005.

ASM/RXTE consists of three proportional counters, each of which has a $6^\circ \times 90^\circ$ FOV, and covers about 80% of the sky during one full rotation, which takes about 1.5 hr. The ASM data (2–12 keV) are publicly available. The light curves come in three energy bands: 1.5–3, 3–5, and 5–12 keV, which are used to estimate the X-ray spectrum in this work. For Mrk 421 and Mrk 501 the daily flux at energies 2-12 keV is provided up to the middle of 2010.

MAXI is a highly sensitive large FOV instrument onboard the International Space Station, working at energies 0.5-30 keV. It started to monitor sky in August 2009. The light curves at 2–20 keV for specific sources are publicly available. The light curves come in three energy bands: 2–4, 4–10, and 10–20 keV. The two low energy bands are used to estimate the X-ray spectrum in this work.

XRT/Swift is a focusing X-ray telescope with energy range from 0.2 to 10 keV. In Windowed Timing mode, XRT data in four time windows are available and the exposure time is about 1 ks in each window. The XRT data set was processed with the XRTDAS software package (v.2.6.0) following the standard recommendations. The XRT average spectrum in the 0.5–10 keV energy band was fitted using the XSPEC package (v.12.7.0). We adopted a power-law model for the photon-flux spectral density, with an absorption hydrogen-equivalent column density fixed to the Galactic value in the direction of the source, namely $1.92 \times 10^{20}$ and $1.55 \times 10^{20} \text{ cm}^{-2}$ for Mrk 421 and Mrk 501, respectively.

3 Results
3.1 Mrk 421

Figure 1 exhibits the X-ray flux light curves of Mrk 421 as detected by BAT/Swift at 15–50 keV. This source enters a flaring phase in the middle of year 2009. The flux is higher than the steady period and there are many flares. During this active phase we denote only three large flares, named as Flare 1, Flare 2 and Flare 3. These flares were also detected by MAXI at 2-10 keV. Flare 2 is associated with the strong VHE $\gamma$-ray activity detected by the VERITAS Observatory on February 17\textsuperscript{10}. The gamma-ray flux as detected by Fermi-LAT is also enhanced during Flare 2. Except Flare 4 and Flare 5, Mrk 421 seems to enter a quiet phase since the middle of 2010 according to Figure 1. In fact, a large $\gamma$-ray flux is detected by Fermi-LAT during the middle of 2012, denoted as Flare 6. During this latter, the X-ray flux also increased by a factor two according to the MAXI result at 2-10 keV.

For all the six flares, the time-averaged SEDs from X-rays to VHE $\gamma$-rays are summarized in Table 1, where a simple power law is assumed, $F$ is the integral flux and $\alpha$ is the spectral index. At X-ray band, only the SED measured by MAXI is listed in Table 1. For comparison, a simultaneous averaged SED over a long-term low state from November 16, 2010 to June 27, 2012, excluding Flare 4, is also presented in Table 1. The flux from Mrk 421 is in a low steady state also according to the soft X-ray light curve measured by XRT/Swift and MAXI.

At X-ray bands, the fluxes during flaring periods enhance about 4–20 times comparing to the low state. The spectra harden during the flaring periods except during Flare 6. In the $\gamma$-ray band, the spectrum index is stable except for Flare 2, during which it hardens. The flux is also stable during Flares 1, 3, 4 and 5. The emission enhanced about three times during Flare 6. In the VHE $\gamma$-ray band, Flare 2 is the largest one with also the hardest spectrum among the six flares. The evolution of spectral indices is similar to that of X-rays. The spectrum of Flare 6 is the softest one. Finally, we can conclude that Flares 1, 3, 4 and 5 are very similar, while Flare 2 and Flare 6 are of different types. These three types may be caused by different intrinsic physical mechanisms. During Flare 2 and Flare 3, also XRT/Swift observed the source, finding that the peak of the first bump is shifted to a higher energy. The SEDs for the six flares are shown in Figure 2 in comparison with that of the long-term low state. It is worth to note that the low state SED obtained in this work is much lower than that obtained by \cite{12} during the first half of 2009.

3.2 Mrk 501

Mrk 501 is stable during a long-term period, and it began a flaring phase since October 2011. Figure 3 exhibits the X-ray flux light curves of Mrk 501 as detected by BAT/Swift at 15–50 keV. According to Figure 3, the flux is higher than the previous quasi-steady state at least up to January 2013. The highest flux appeared between years 2011 and 2012. To study the evolution of the spectra, the data are roughly divided into four epochs, named A, B, C and D. In the soft X-ray band, XRT/Swift has observed this source during all the four epochs. The period from August 2008 to September 2011 is labeled as the steady epoch. For all the epochs, the time-averaged SEDs from X-rays to VHE $\gamma$-rays are summarized in Table 2 and shown in Figure 4 in comparison with the steady state. In the X-ray band, the spectral index is harder during all active phases. A moderate variation is also present in the $\gamma$-ray band, together with an index variation. In the VHE $\gamma$-ray band, the flux enhances up to ~5 times compared with the steady one. The spectra are harder than the long-term steady one. Epoch A has the largest flux and its spectral index is also relatively hard. ARGON-YBJ observations for Epoch A have been reported in \cite{11}.

4 Summary

Mrk 421 and Mrk 501 are very active blazars with frequent variability, composed of many flares. These make these blazars excellent candidates for the study of the jet physics in AGNs. From August 2008 to January 2013, these sources have been simultaneously monitored by ARGON-YBJ, Fermi-LAT and some X-ray satellites. Several flares have been detected from X-rays to VHE $\gamma$-rays. In this paper, we have presented a multi-wavelength spectral evolution of these flares. This is important for further studies on the underlying physics which causes such variations.

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Fig. 3: Three day-averaged light curve of Mrk 501 at 15–50 keV measured by BAT/Swift. The vertical dashed lines indicate the four epochs analyzed in this paper. All the errors are statistical at 1σ.

Fig. 4: SED of Mrk 501 derived during the four epochs (blue points) and the long-term low state (red points). The magenta arrows indicate the 95% confidence level flux upper limits set by Fermi-LAT and ARGO-YBJ. The grey points indicate the SED obtained by [13].

Table 2: SED results for Mrk 501, the unit for integral flux $F$ is (ph cm$^{-2}$ s$^{-1}$)

<table>
<thead>
<tr>
<th>Epoch</th>
<th>MJD</th>
<th>$F_{0.5-10\text{keV}}$ ($\times 10^{-5}$)</th>
<th>$\alpha$</th>
<th>$F_{0.1\text{TeV}}$ ($\times 10^{-8}$)</th>
<th>$\alpha$</th>
<th>$F_{&gt;1\text{TeV}}$ ($\times 10^{-12}$)</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>55851–55887</td>
<td>8.08±0.06</td>
<td>1.700±0.010</td>
<td>6.40±0.20</td>
<td>1.64±0.02</td>
<td>37.3±6.9</td>
<td>2.27±0.15</td>
</tr>
<tr>
<td>B</td>
<td>55887–55939</td>
<td>11.60±0.05</td>
<td>1.704±0.006</td>
<td>7.98±0.34</td>
<td>1.56±0.02</td>
<td>27.2±5.2</td>
<td>2.71±0.22</td>
</tr>
<tr>
<td>C</td>
<td>55939–55979</td>
<td>12.98±0.08</td>
<td>1.758±0.008</td>
<td>9.56±1.54</td>
<td>1.83±0.08</td>
<td>19.4±5.8</td>
<td>2.40±0.35</td>
</tr>
<tr>
<td>D</td>
<td>55979–56197</td>
<td>9.66±0.02</td>
<td>1.773±0.003</td>
<td>6.33±0.19</td>
<td>1.72±0.01</td>
<td>9.2±2.6</td>
<td>2.23±0.22</td>
</tr>
<tr>
<td>Steady</td>
<td>54683–55841</td>
<td>5.05±0.01</td>
<td>1.995±0.002</td>
<td>5.22±0.15</td>
<td>1.77±0.02</td>
<td>6.9±1.3</td>
<td>2.81±0.18</td>
</tr>
</tbody>
</table>

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