An all sky survey for flaring gamma ray sources with ARGO-YBJ data

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Abstract: The ARGO-YBJ detector is characterized by a high duty cycle and a wide field of view. Therefore, it is capable of carrying out a continuous all sky survey for VHE gamma-ray flares. Based on a careful data quality check, using surrounding window method to estimate the background, an all sky survey for VHE gamma-ray flares is implemented using the ARGO-YBJ data from December 2008 to October 2010.

Keywords: Flaring gamma-ray sources, All sky survey, ARGO-YBJ

1 Introduction

Most of VHE extragalactic sources, around 30, belong to a blazar class of active galactic nuclei (AGNs) with a common feature of BL Lac objects. The emission from blazars is highly variable and is characterized by a flaring behavior, in which the flux increases dramatically on various time scales, even down to the scale of hours. Searching and observing VHE gamma flares is very important in gamma-ray astronomy especially in measuring of extragalactic background lights and in constraint of acceleration models.

The high duty cycle (∼86%) and the wide aperture (∼2 sr) of ARGO-YBJ allows the detection of flaring behavior associated with these AGNs, especially during daytime transits when the Imaging Atmospheric Cherenkov Telescopes do not work. Two very interesting flaring events have been observed by ARGO-YBJ. First, in June 2008 [1], ARGO-YBJ successfully observed flares of Mrk 421 on a timescale of 3 days, at that time IACTs cannot do so due to the moonlight. Second, in February 2010, an excess signal (around 4 s.d.) from Mrk 421 was captured within a one-day transit [2]. These observations confirm that ARGO-YBJ has the ability in all sky survey for gamma-ray flares from variable sources.

The paper introduces a work on all sky survey for gamma-ray flares. Section 2 briefly introduces the experiment setup. The details of survey procedure are described in section 3, including the data quality check, the event selection criteria, the time binnings, the sky divisions, the background determination and the candidate selection. Results of the survey are finally presented in section 4.

2 ARGO-YBJ experiment

The ARGO-YBJ detector is located at the Yang-Ba-Jing Cosmic Ray Observatory (30.11°N, 90.53°E), Tibet, China, at an altitude of 4300 m a.s.l., corresponding to a vertical atmospheric depth of 606 g/cm². It consists of a single layer of Resistive Place Chambers (RPCs), with each RPC (2.8 × 1.25 m²) divided into 10 basic detection units called PADs (55.6 × 61.8 cm²). Each PAD consists of 8 digital readout strips. Twelve RPCs are grouped into a cluster (5.7 × 7.6 m²). The central carpet (78 × 74 m²) of the detector is fully covered by 130 clusters, whereas 23 clusters form a guard ring surrounding the central carpet. The whole array covers a total area of about 11,000 m².

To extend the dynamic range, a charge read-out layer has been implemented by installing to each RPC two large-size pads called the Big Pad (140 × 122.5 cm²) [3]. Two independent DAQ systems are implemented in the detector: the scale mode and the shower mode. In this work, only the data from the shower mode has been used. The trigger condition refers to the number of fired pads greater than 20 within the 420 ns triggering window, whereas the trigger rate is about 3.5 kHz [4]. The completed ARGO-YBJ has been collecting data since November 2007.

3 All sky survey

3.1 Data quality check

The timescale of flares from VHE gamma-ray Blazar is short, ranging from several hours to several days. In such a short timescale, the detection is apt to be affected by abrupt
abnormal situation of the detector, either giving an inaccurate estimation of the signal intensity, or reporting a false flare. Therefore, rigorous data quality checks are obligated. First, the logbook of the data-taking is read to remove runs apparently in bad conditions, like runs with gas or electronics problems. Not all the bad runs could be covered by the logbook; then a more stringent check based on distributions of a variety of parameters, considered to reflect the running status of the detector, is carried out. Two crucial parameters, the overall event rate and the averaged $\chi^2$ of the shower front fitting, are chosen for the study. The procedure of overall rate checking should not bring any vital bias, because the signals from any flaring point source contribute only a marginal enhancement to the overall event rate, unless it is strong in an unexpected level that can be detected with a significance of thousands of standard deviations. The distributions of these parameters in two time scales – every run and every minute – are studied. After that, three levels of event selections, the period level, the run level and the slice level, are applied to the data. If the values of any parameter, averaged in the run scale, of a batch of consequent runs in a period lasting for a couple of days are far away (5 s.d.) from the linear fitting of all runs, the data in this period is removed; Similar as above, if that of a single run are far away (5 s.d.) from the moving average of nearby days, the run is removed; If the value of any parameter, averaged in the minute scale, in a time slice of 1 minute, is far away (5 s.d.) from the fitted average of nearby slices (spanning a day), the slice is removed. A total of 9.52% of events are excluded from all above levels of data quality checks.

ARGO-YBJ data from December 2007 to October 2010, amounting to about 170 M events, are used for the all sky survey. Two event selection criteria are used, as follows:

(a) zenith angle: $< 60^\circ$;

(b) Hit multiplicity: $> 20$, $> 40$, $> 60$, $> 100$.

Several hit multiplicity thresholds are particularly adopted in this study, for the purpose of better detecting sources with different spectra.

### 3.2 Time binnings

The purpose of the work is to search flaring signals from VHE gamma-ray sources. The whole running period of the ARGO-YBJ is divided into time windows with equal length of $2^n$ minutes ($n$ is from 7 to 14). That is to say, the flares are surveyed with time scales ranging from 2.1 hours to 11.4 days. All these time binnings start at 00:00:00, MJD 53736 (January 1, 2006).

### 3.3 Sky cells

The whole sky is partitioned into rectangular cells in the following manner: the declination is divided into $n$ bands $\delta_i (i = 1, 2, \ldots, n)$ with equal width $\Delta \delta = 180^\circ / n$. For each declination band $\delta_i$, the right ascension is further divided into $m_i$ cells with equal width $\Delta \alpha_i$, where $m_i$ is the best integer to satisfy $360^\circ / m_i = \Delta \delta / \cos \delta_i$ and $\Delta \alpha_i = 360^\circ / m_i$. $\Delta \delta$ is the only parameter used for defining the sky cells. Usually it should be set to match the optimized bin size. Before doing that, the following considerations must be concerned:

- A flaring source may not locate at the center of a sky cell due to the fact that the division of the sky is applied beforehand, and not optimized for any source;
- The significance changes slowly with the width of the sky cell according to the simulation;
- Decreasing or increasing the sizes of the sky cells in several iterations, a source in an arbitrary location have rather big chance to approach the center of a cell, being detected with similar significance as the case an optimized cell around it.

Therefore, three cell sizes for each hit multiplicity threshold are applied to the survey. Besides the size near to the optimized value, another two, approximately 1.4 and 1/1.4 times the optimized value, are adopted. Table 1 shows the sky cell sizes for every hit multiplicity thresholds.

To ensure an accurate determination of background, the sky cells are only effective while center of them being of zenith angle less than $45^\circ$.

### Table 1: Selection of cell sizes for 4 hit multiplicity thresholds. Size A, B, C are the 3 selected sky cell sizes.

<table>
<thead>
<tr>
<th>Hit multiplicity size</th>
<th>Optimized size</th>
<th>Size A</th>
<th>Size B</th>
<th>Size C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt; 20$</td>
<td>2.55</td>
<td>2.5</td>
<td>1.8</td>
<td>3.6</td>
</tr>
<tr>
<td>$&gt; 40$</td>
<td>2.43</td>
<td>2.5</td>
<td>1.8</td>
<td>3.6</td>
</tr>
<tr>
<td>$&gt; 60$</td>
<td>1.93</td>
<td>2.0</td>
<td>1.5</td>
<td>3.0</td>
</tr>
<tr>
<td>$&gt; 100$</td>
<td>1.57</td>
<td>1.5</td>
<td>1.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

### 3.4 Background determination

The surrounding region method is used for the determination of the background. That means that every sky cell is assigned a hollow background region around it, from which the background can be determined, as shown in Figure allsky. In brief, this method relies on the fact that the acceptance ratio, $1/R$, between a center cell and the hollow region around it in a fixed direction with respect to the detector, remains nearly constant, unless a very big hardware change to the detector occurs. The ratio $R$ can be calibrated by the experimental data over a long stable period. By counting the number of events in the background region within the same time interval and by knowing $R$, the expected number of background events in the cell of interest can be calculated. This method is discussed in details in [5]. After that, the Li-Ma prescription [6] is adopted to calculate the significance
3.5 Selection of candidates

In this analysis, there are 4 hit multiplicity thresholds; For each hit multiplicity thresholds, there exist 3 different sky cell sizes; And for every pair of threshold and cell size, 8 time binnings are implemented. So there are totally $4 \times 3 \times 8 = 96$ assemblies of sky surveys. For a given assembly, the number of effective time bins is counted for each sky cell individually, and the corresponding significance for every effective time bin is calculated — the effectiveness here means that there is at least 1 event in the background region. Only the time bin with the most significant excess is selected. The significances of selected time bins for all sky cells of an assembly compose a sky map, named a sky map of the most significant excesses; 96 maps in total, one of which is shown in figure 2.

With this method, the Mrk 421 flares occurred in this period have not been detected with enough significances, attributed to too many trials in the survey and no optimisation in space and time made for these flares. The significances given by this survey are 2.22 s.d. (assembly of hit multiplicity threshold 100, sky cell size 2.0°, time binning 212 minutes) and 3.93 s.d. (assembly of hit multiplicity threshold 100, sky cell size 2.0°, time binning 212 minutes), for the Mrk 421 flares in June 2008 and February 2010, respectively.

The distribution of chance occurrence of the top 1000 most significant excesses is shown in figure 3. The cumulative (integral) distribution of the these entries shall appear along a straight line, from (1,1) to (1000,1000), if all these excesses come from pure background fluctuations. Similar to the selection of excesses, the top 1000 most significant deficits can be obtained from the analysis too, whose distribution is shown in the top panel of figure 4. The cumulative distribution is much far away from the expectation, due to the shadowing effect of the Sun. The posi-

od. Then taking all the $N_{\text{map}} = 96$ sky maps (trials) into account, the final chance occurrence $Q_{\text{final}}(c_i, M_j)$ for the sky cell is

$$Q_{\text{final}}(c_i, M_j) = Q(c_i, M_j) \cdot N_{\text{map}},$$

which is then converted to chance probability $P_{\text{final}}(c_i, M_j)$ with

$$P_{\text{final}}(c_i, M_j) = 1 - \exp \left( -Q_{\text{final}}(c_i, M_j) \right).$$

If a sky cell had exhibited a chance probability less than 1%, that is to say, 1 occurrence per 300 years’ data taking due to fluctuations, we would think it is significant and then investigate it further.

4 Result

The chance probability of every sky cell is calculated by formulae 1–3 and sorted in an order from small to big. Survey details of the top 10 most significant excesses is given in table 2.

Table 2: Details of the top 10 excesses with the smallest chance probability.

<table>
<thead>
<tr>
<th>$N_{\text{hit}}$</th>
<th>cell size (°)</th>
<th>time binning (min)</th>
<th>significance (s.d.)</th>
<th>$N_{\text{eff}}^{\text{time-bin}}(c_i, M_j)$</th>
<th>$N_{\text{eff}}^{\text{sky-cell}}(M_j)$</th>
<th>$Q_{\text{final}}$</th>
<th>$P_{\text{final}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 40</td>
<td>2.5</td>
<td>$2^7$</td>
<td>6.12</td>
<td>5221</td>
<td>4040</td>
<td>0.94</td>
<td>0.61</td>
</tr>
<tr>
<td>&gt; 40</td>
<td>2.5</td>
<td>$2^8$</td>
<td>5.81</td>
<td>2852</td>
<td>4040</td>
<td>3.54</td>
<td>0.97</td>
</tr>
<tr>
<td>&gt; 20</td>
<td>1.8</td>
<td>$2^{10}$</td>
<td>5.78</td>
<td>1438</td>
<td>7752</td>
<td>3.90</td>
<td>0.98</td>
</tr>
<tr>
<td>&gt; 20</td>
<td>3.6</td>
<td>$2^{10}$</td>
<td>5.52</td>
<td>1404</td>
<td>1940</td>
<td>4.32</td>
<td>0.99</td>
</tr>
<tr>
<td>&gt; 20</td>
<td>3.6</td>
<td>$2^{12}$</td>
<td>5.28</td>
<td>370</td>
<td>1940</td>
<td>4.57</td>
<td>0.99</td>
</tr>
<tr>
<td>&gt; 20</td>
<td>2.5</td>
<td>$2^{13}$</td>
<td>5.28</td>
<td>188</td>
<td>4040</td>
<td>4.67</td>
<td>0.99</td>
</tr>
<tr>
<td>&gt; 20</td>
<td>1.8</td>
<td>$2^9$</td>
<td>5.80</td>
<td>2134</td>
<td>7752</td>
<td>5.32</td>
<td>1.00</td>
</tr>
<tr>
<td>&gt; 60</td>
<td>3.0</td>
<td>$2^{14}$</td>
<td>4.90</td>
<td>95</td>
<td>2808</td>
<td>12.2</td>
<td>1.00</td>
</tr>
<tr>
<td>&gt; 100</td>
<td>2.0</td>
<td>$2^8$</td>
<td>5.68</td>
<td>3227</td>
<td>6205</td>
<td>12.8</td>
<td>1.00</td>
</tr>
<tr>
<td>&gt; 60</td>
<td>2.0</td>
<td>$2^{13}$</td>
<td>5.12</td>
<td>188</td>
<td>6205</td>
<td>16.8</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Y. CHEN et al. AN ALL SKY SURVEY FOR FLARING GAMMA-RAY SOURCES WITH ARGO-YBJ DATA

Figure 3: Distribution of chance occurrence of the top 1000 most significant excesses. The cumulative distribution and its expectation, a straight line, is drawn also for a comparison.

Figure 4: Distribution of chance occurrence of the top 1000 most significant deficits. The sky cells hosting the Sun are excluded in the bottom panel.

5 Flux upper limit

Due to no significant excess has been observed, a flux upper limit calculation is made for all 96 sky maps, based on the acceptance of the detector obtained from a simulation. For each sky map, the statistics of the maximum significance sky cell among every declination band is used, representing the value of this specific band. The details of the method can be found in [7]. Finally these flux upper limits are converted into values in the unit of Crab, which means the flux of Crab Nebula, which is $4.2 \times 10^{-11} E^{-2.57} \text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$.

As an example, the flux upper limits for a particular sky map, as a function of declination band, is shown in figure 5.

Figure 5: Flux upper limits for every declination band of one of the sky maps. The hit multiplicity $> 60$, cell size 1.5 degree, time binning $2^{11}$ minutes.

6 Conclusion

After a careful check to the data quality, an all sky survey for gamma ray flares with the ARGO-YBJ data is implemented. No significant excess has been found yet. Flux upper limits are finally given for every declination band of the 96 sky maps.

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References