TeV gamma-ray survey of the northern sky using the ARGO-YBJ experiment

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Abstract: The ARGO-YBJ experiment is an extensive air shower array that monitored the northern $\gamma$-ray sky at energies above 0.3 TeV from 2007 November to 2013 January. In this paper we present the result of a sky survey in the declination band from $-10^\circ$ to $70^\circ$, using the data recorded in more than five years. With a cumulative sensitivity ranging from 0.24 to $\sim$1 Crab units, depending on the declination, six sources have been observed with a statistical significance greater than 5 standard deviations. Several interesting hotspots are also reported as potential $\gamma$-ray emitters. The features of each source are presented and discussed. Additionally, 95\% confidence level upper limits to the flux from all sky regions are presented, which are more stringent than any previously published limits for TeV $\gamma$-ray all-sky surveys. The specific upper limits for 663 GeV $\gamma$-ray AGNs inside the ARGO-YBJ field of view are presented. The effect of the absorption of $\gamma$-rays due to the interaction with the extragalactic background light are estimated.

Keywords: all sky survey, gamma ray observation, ARGO-YBJ

1 Introduction

In the past two decades, VHE $\gamma$-ray astronomy progressively opened a new window to probe the non-thermal universe and the extreme physics processes in astrophysical sources. Up to now, almost 150 very high energy (VHE) $\gamma$-ray sources have been observed by ground-based $\gamma$-ray detectors. Such an achievement is mainly due to the successful operation of image atmospheric Cherenkov telescopes (IACTs), such as H.E.S.S., MAGIC, VERITAS and CANGAROO, which made most of the discoveries when searching for counterparts of sources observed at lower energies. To achieve an overall view of the universe in the VHE $\gamma$-ray band, an unbiased sky survey is needed, like what has been done by Fermi and its predecessor EGRET at GeV $\gamma$-ray energies, which detected 1873 and 271 objects, including 575 and 170 still unidentified, respectively \cite{1,2}. Due to the small field of view (FOV) and the low duty cycle, IACTs are not suitable to perform a comprehensive sky survey. Although with a sensitivity lower than that of IACTs, extensive air shower arrays, such as Tibet AS\textsuperscript{γ}, Milagro and ARGO-YBJ, are the only choice to perform a continuous sky survey at VHE energies. This paper reports the results of a sky survey made by ARGO-YBJ, that monitored the sky between declinations $-10^\circ$ and $70^\circ$ for more than 5 years.

2 The ARGO-YBJ experiment

The ARGO-YBJ experiment, located at the Yangbajing Laboratory (Tibet, China, 90.5° east, 30.1° north), is designed for VHE $\gamma$-ray astronomy and cosmic ray observations. It consists of a $\sim$74×78 m$^2$ carpet made of a single layer of Resistive Plate Chambers (RPCs) with $\sim$92\% of active area, surrounded by a partially instrumented ($\sim$20\%) area “guard ring” up to $\sim$100×110 m$^2$. The apparatus is made of 18360 “pads” of size 55.6×61.8 cm$^2$ which are the space-time “pixels” of the detector. The showers hitting a number of pads $N_{pad} \geq 20$ in the central carpet generate the trigger. More details about the detector and the RPC performance can be found in \cite{3,4}. The central carpet started taking data in July 2006, while the “guard ring” was merged into the DAQ stream in November 2007. The trigger rate is 3.5 kHz with a dead time of 4\% and the average duty cycle is higher than 86\%.

The ARGO-YBJ data used in this analysis were collected from November 2007 to January 2013, with a total observation time of 1670.45 days. For the analysis presented in this paper, only the events with a zenith angle less than $50^\circ$ are used. An event selection based on the shower reconstruction parameters is applied to achieve a better angular resolution. The total number of selected events is $2.99 \times 10^{11}$. They are used to fill a map in celestial coordinates (right ascension and declination) with $0.1^\circ \times 0.1^\circ$ bins, covering the declination band from $-10^\circ$ to $70^\circ$.

To extract the excesses of $\gamma$-induced showers, the analysis procedure described in \cite{5} has been applied. The effects of the large scale anisotropy have been removed according to the method described in \cite{5}. To reduce the contamination from the Galactic Plane diffuse $\gamma$-ray emission \cite{6}, a specific correction procedure has been adopted in the region of galactic latitude $|b| < 2^\circ$. The sky map is smoothed weighting the events according to the detector Point Spread Function. The Li-Ma formula \cite{7} is used to estimate the statistical significance.

3 Results

3.1 Sky survey

The significance distribution of the whole map bins is shown in Fig.1. The distribution, with a mean value of 0.002 and $\sigma=1.02$, closely follows a standard Gaussian distribution except for a tail with large positive values, due to the excesses from several gamma ray emission regions, shown in Fig.2. Table 1 lists the locations of all the regions with significance greater than 4.5 standard deviations (S.D.). For each independent region, only the coordinates of the pixel with the highest significance are given. Based on the distribution of negative points (Fig.1), a significance
Figure 1: Significance distribution of the whole sky map (thick solid line). The thin solid line represents the best Gaussian fit. The significance distribution of the Galactic Plane region with \( |b| < 2^\circ \) and \( 20^\circ < l < 90^\circ \) is shown by the thick dotted line. The thin dotted line represents the best Gaussian fit for the same region.

Table 1: Location of the excess regions

<table>
<thead>
<tr>
<th>Name</th>
<th>Ra (deg)</th>
<th>Dec (deg)</th>
<th>S (S.D.)</th>
<th>Associated TeV Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0409−0627</td>
<td>62.35</td>
<td>-6.45</td>
<td>4.8</td>
<td>Crab Nebula</td>
</tr>
<tr>
<td>J0535+2203</td>
<td>83.75</td>
<td>22.05</td>
<td>20.8</td>
<td>Mrk 421</td>
</tr>
<tr>
<td>J1105+3821</td>
<td>166.25</td>
<td>38.35</td>
<td>14.1</td>
<td>Mrk 501</td>
</tr>
<tr>
<td>J1654+3945</td>
<td>253.55</td>
<td>39.75</td>
<td>9.4</td>
<td>HESS J1841-055</td>
</tr>
<tr>
<td>J1839−0627</td>
<td>279.95</td>
<td>-6.45</td>
<td>6.0</td>
<td>HESS J1908+063</td>
</tr>
<tr>
<td>J1907+0627</td>
<td>286.95</td>
<td>6.45</td>
<td>5.3</td>
<td>HESS J1908+063</td>
</tr>
<tr>
<td>J1910+0720</td>
<td>287.65</td>
<td>7.35</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>J1912+1026</td>
<td>288.05</td>
<td>10.45</td>
<td>4.2</td>
<td>HESS J1912+101</td>
</tr>
<tr>
<td>J2021+4038</td>
<td>305.25</td>
<td>40.65</td>
<td>4.3</td>
<td>VER J2019+407</td>
</tr>
<tr>
<td>J2031+4157</td>
<td>307.95</td>
<td>41.95</td>
<td>6.1</td>
<td>MGRO J2031+41</td>
</tr>
<tr>
<td>J1841-0332</td>
<td>280.25</td>
<td>-3.55</td>
<td>4.2</td>
<td>TeV J2032+4130</td>
</tr>
</tbody>
</table>

3.2 Observed sources

In the following, a detailed presentation of the sources listed in Table 1 is given.

ARGO J0535+2203, detected at 21 S.D., is positionally consistent with the Crab Nebula. The location is 0.08° from the pulsar, consistent with the statistical error. The SED derived from the ARGO-YBJ data is \( \frac{d\Phi}{dE} = (3.05 \pm 0.17) \times 10^{-11} (E/1 \text{ TeV})^{-2.61 \pm 0.06} (\text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}) \), consistent, within the errors, with the results obtained by other experiments.

ARGO J1105+3821, detected at 14 S.D., is positionally consistent with the blazar Mrk 421. This is an active source and many outbursts have been observed by ARGO-YBJ in the past years [8, 5]. Its five-year average flux above 1 TeV is \( \sim 0.71 I_{\text{Crab}} \).

ARGO J1654+3945, detected at 9 S.D., is positionally consistent with the blazar Mrk 501. This source entered into an active phase in October 2011, according to ARGO-YBJ observations [2]. Its five-year average flux above 1 TeV is \( \sim 0.51 I_{\text{Crab}} \).

ARGO J1839−0627 is an extended source. Most of the excess overlaps the extended region of the unidentified source HESS J1841-055 even if the peak position is slightly displaced from the center of HESS J1841-055 [10]. The flux measured by ARGO-YBJ is higher than that determined by HESS. A detailed discussion about this object can be found in [11].
ARGO J1907+0627 is closely connected to ARGO J1910+0720. ARGO J1907+0627 is positionally consistent with HESS J1908+063 [12], while ARGO J1910+0720 is completely outside the extended region of HESS J1908+063. In a previous work, ARGO J1907+0627 and ARGO J1910+0720 have been considered as a unique source, identified as the extended source MGRO J1908+06 [13]. The flux determined by ARGO-YBJ was consistent with that of Milagro but higher than that of HESS J1908+063. Its extended size is also marginally larger than HESS J1908+063. Therefore, MGRO J1908+06 could be the blend of ARGO J1907+0627 and ARGO J1910+0720. ARGO J1907+0627 is positionally consistent with the pulsar PSR J1907+0602, and could be the associated pulsar wind nebula. Very close to ARGO J1910+0720, a counterpart in the hard X-ray band, SWIFT J1910.8+0739 (4U 1909+07) (Ra=287.699°, Dec=7.598°) [14], is found. This X-ray source is a high mass x-ray binary (HMXB), a type of source identified as VHE γ-ray emitter. ARGO J1910+0720 is detected at only 4.3 S.D., and the nearby source ARGO J1907+0627 could contribute to the observed excess. With the present statistic we cannot exclude the possibility of a background fluctuation. However, it is an interesting region for follow-up observations with more sensitive instruments.

ARGO J1912+1026, detected with 4.2 S.D., is positionally consistent with HESS J1912+101 [15]. Assuming a power law spectrum, the spectral index obtained by ARGO-YBJ is -2.68±0.35 which is consistent with -2.7±0.2, obtained by HESS. However the flux above 1 TeV is 23% I\textsubscript{Crab}, much higher than the value 9% I\textsubscript{Crab} determined by HESS. We reported a similar disagreement for the source HESS J1841-055.

ARGO J2021+4038, in the Cygnus region, is positionally consistent with VER J2019+407 [16], whose flux is only 3.7% I\textsubscript{Crab}, but the nearby extended source ARGO J2031+4157 could contribute to most of the excess, as shown in Fig.3.

ARGO J2031+4157 is a very extended source located in the Cygnus region, positional consistent with MGRO J2031+41 and TeV J2032+4130. Also in this case the measured flux is higher than that measured by IACTs. A detailed report on this region can be found in [17].

ARGO J0409−0627, detected at 4.8 S.D., is outside the Galactic plane. No counterpart at lower energies, including GeV γ-ray and X-ray bands, is found. Its post-trial significance should be less than 3 standard deviations.

Figure 3: Significance map of the Galactic Plane region with |b| < 10° and 20° < l < 90° obtained by the ARGO-YBJ experiment. The circles indicate the position of all the known VHE sources. The open stars mark the location of the GeV sources of the second Fermi-LAT catalog [1].

Figure 4: 95% C.L. flux upper limits for energy above 500 GeV, averaged over the right ascension, as a function of the declination. The different curves indicate a different power-law spectral index.

ARGO J1841-0332 is detected at 3.4 S.D. using events with N\textsubscript{pad} > 20 and at 4.2 S.D. using events with N\textsubscript{pad} > 100. No VHE γ-ray counterpart is found in this region, while it is adjacent to the VHE γ-ray source HESS J1843-033. Other five GeV γ-ray sources surround this region as shown in Fig.3. An observation with improved sensitivity is mandatory to clarify this possible TeV emission.

3.3 Sky upper limits

Excluding the sources listed in Table 1, we can set upper limits to the γ-ray flux from all other directions in the sky.

To estimate the response of the ARGO-YBJ detector we simulated a source located at different declinations, with a power law spectrum, in the energy range 10 GeV - 100 TeV and different spectral indexes. The statistical method given in [18] is used to calculate the upper limit on the number of signal events at 95% C.L. from each bin. The number of events is transformed into a flux using the results of the simulation. The 95% C.L. upper limits to the flux of γ-rays with energies above 500 GeV for each bin are obtained. The upper limits as a function of the declination are shown in Fig.4 for different photon spectral indexes. The limits range between 9% and 44% I\textsubscript{Crab} and are the lowest obtained so far. The lowest limit for a spectral index −2.0 (−3.0) is 5% (9%) I\textsubscript{Crab}, where the Crab unit is defined as 5.77×10⁻¹¹ cm⁻² s⁻¹.
With an energy threshold lower than any other previous extensive air shower arrays, ARGO-YBJ is suitable for the observation of AGNs, which dominate the extra-galactic sky. According to the Fermi-LAT second GeV γ-ray AGN catalog. 663 AGNs are within the ARGO-YBJ FOV [19]. Fig.5 shows the comparison between ARGO-YBJ flux upper limits and the fluxes obtained by extrapolating at TeV energies the SEDs measured by Fermi-LAT at 1-100 GeV. The extrapolation is performed assuming the spectral index to steepen by 0.5 at 100 GeV. This spectral behaviour is physically motivated because radiative cooling is expected to modify the electron power-law index by 1 unit and correspondingly the γ-ray index by 0.5. For convenience, the fluxes shown in Fig.5 have been transformed into differential fluxes at 1 TeV. As can be seen from Fig.5, for 135 AGNs out of 663 the calculated upper limits are lower than the extrapolated fluxes suggesting a steeper spectra above 100 GeV. Such an effect could be due to the absorption of photons by the extragalactic background light (EBL). By applying the model proposed in [20], the effect of the EBL absorption on the upper limits has been evaluated, and the absorption factor is shown as a function of the declination, for different source redshifts.

4 Summary

In this paper the most sensitive survey of the Northern sky in the declination band -10° – 70° obtained by the 5-years ARGO-YBJ data has been presented. With a cumulative sensitivity ranging from 0.24 to ~1 Crab flux, depending on the declination, six sources have been observed with a statistical significance greater than 5 standard deviations. These sources are associated to well known TeV γ-ray emitters. Evidence for a possible TeV emission from 5 hotspots is also reported. Three sources out of 5 cannot be associated to known sources and are potential new TeV emitters. Of particular interest the possible source ARGO J1910+0720, positionally coincident with a high mass x-ray binary. Observations of these hotspots by IACTs are expected. These sources are associated to well known TeV γ-ray emitters. Evidence for a possible TeV emission from 5 hotspots is also reported. Three sources out of 5 cannot be associated to known sources and are potential new TeV emitters. Of particular interest the possible source ARGO J1910+0720, positionally coincident with a high mass x-ray binary. Observations of these hotspots by IACTs are suggested. The 95% C.L. upper limits to the γ-ray flux from all directions are also reported. The integral flux limits above 0.5 TeV vary from 0.09 to 0.44 Crab units for a Crab-like source, depending on the declination. The limits set by ARGO-YBJ in this work are the lowest so far available. Specific upper limits for 663 GeV γ-ray AGNs are also presented.

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References