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 with full coverage RPC detectors located at Yangbajing (4300 m asl, Tibet, China). It is operated with full duty cycle (> 90%) and a large field of view (\(\approx 2\)sr). With a sensitivity of 0.5 Crab unit per year, ARGO-YBJ continuously monitors the entire overhead sky at \(\gamma\)-ray energy above 0.3 TeV. In the talk, we will present the survey result of the northern sky (between declinations of -10\(^\circ\) and 70\(^\circ\)) from an analysis of 4.5 year of the ARGO-YBJ data (2006 June-2011 June). There are four known TeV sources observed with significance greater than 5 S.D.. The significance from Crab Nebula is more than 16 S.D.. A 90% confidence level upper flux limits for all directions in the sky are also presented, which vary from 0.09 and 0.53 Crab unit for Crab-like point source.

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

1 Introduction

In the last decade, great advances have been made in ground-based \(\gamma\)-ray astronomy and more than 100 very high energy (VHE) \(\gamma\)-ray sources have been observed. A new window using VHE \(\gamma\)-rays is progressively established to probe the non-thermal universe and the extreme physics process on the astrophysical sources. The VHE \(\gamma\)-rays are the emissions of the relativistic particles, which are accelerated by the astrophysical shocks that are widely believed to exist in the pulsar wind nebulae (PWN), shell type supernova remnants (SNR), active galactic nuclei (AGN) and so on. These shocks may accelerate protons or electrons. Relativistic electrons can scatter the low energy photons to VHE band, i.e. Inverse Compton (IC) emission, while relativistic protons would lead to a hadronic cascades and VHE \(\gamma\)-ray are generated by the decay of secondary \(\pi^0\) meson. Hence, VHE \(\gamma\)-ray observations are also important in understanding the origin and acceleration of cosmic rays.

Up to now, the number of VHE \(\gamma\)-ray sources is 107, which includes 61 Galactic sources and 46 extragalactic sources [1]. Most of the identified Galactic sources belong to PWN, SNR, and binary systems, however, about one third of the Galactic sources are still unidentified. The extragalactic sources are mainly composed of AGN including the BL Lac type objects and flat spectrum radio quasars. 3 radio galaxies and 2 starburst galaxies are also observed. Due to the absorption by the extragalactic background light (EBL), which causes a substantial reduction of the flux, VHE \(\gamma\)-ray observations are limited to the nearby sources. The most distant source to date is 3C 279 with \(z=0.536\) [2].

Recent advances in VHE \(\gamma\)-ray observation are mainly attributed to the successful operation of image atmospheric Cerenkov telescopes (IACTs), such as H.E.S.S., MAGIC, VERITAS and CANGAROO, which made most of the discovery when searching for counterparts to sources discovered at lower energies. To achieve an overall view of the universe in VHE \(\gamma\)-ray band, an unbiased sky survey is needed just like what have been done by Fermi and its predecessor EGRET at GeV \(\gamma\)-ray band, which detect 1451 and 271 objects including 630 and 170 unidentified, respectively [3, 4]. The H.E.S.S. collaboration has made great progress in surveying the inner part of the Galactic plane, which leads to the discovery of 14 previously unknown sources [5], however, due to the limits of small field of view (FOV) and low duty cycle, the IACTs are difficult to perform a comprehensive sky survey. As a result, although the sensitivity is lower than that of IACT, extensive air shower (EAS) array, such as the Tibet AS\(\gamma\), Milagro and ARGO-YBJ experiments, is the only one choice to perform a sky survey at VHE band. To date, several surve-ys of the VHE sky have been performed by ACT in 1989 [6], AIROBICC in 2002 [7], Milagro in 2004 [8] and Tibet AS\(\gamma\) in 2005 [9]. The latter two surveys resulted in the successful observation of \(\gamma\)-ray emission from Crab Nebula and Mrk421. The best upper limits at energy above 1 TeV are around 275~600 mcrab achieved by the Milagro experiment. In 2007, Milagro updated their survey of the Galactic plane and 3 new extent sources are discovered [10]. As an independent experiment, the ARGO-YBJ detector has a better sensitivity than any previous EAS array at 1 TeV and is continuously monitoring the northern sky with declinations from -10\(^\circ\) to 70\(^\circ\). This work attempts to
present the TeV γ-ray survey of the northern sky using the 4.5-year data of ARGO-YBJ and set more stringent limits than previous surveys.

2 The ARGO-YBJ experiment

The ARGO-YBJ experiment, located in Tibet, China at an altitude of 4300 m a.s.l., is the result of a collaboration among Chinese and Italian institutions and is designed for VHE γ-ray astronomy and cosmic ray observations. The detector consists of a single layer of Resistive Plate Chambers (RPCs). One hundred thirty clusters (a cluster composed of 12 RPCs ) are installed to form a carpet of about 5600 m² with an active area of ∼93%. This central carpet is surrounded by 23 additional clusters (“guard ring”) to improve the reconstruction of the shower core location. The total area of the array is 110 m × 100 m. More details about the detector and the RPC performance can be found in [11, 12]. The high granularity of the apparatus permits a detailed spatial-temporal reconstruction of the shower profile and therefore the incident direction of the primary particle. The arrival time of the particles is measured by Time to Digital Converters (TDCs) with a resolution of approximately 1.8 ns. This results in an angular resolution of 0.2 degree for showers with energy above 10 TeV and 2.5 degree at approximately 100 GeV . In order to calibrate the 18,360 TDC channels, an off-line method [13] has been developed using cosmic ray showers. The calibration precision is 0.4 ns and the procedure is applied every month [14].

The central 130 clusters began taking data in 2006 June, and the “guard ring” was merged into the DAQ stream in 2007 November. The trigger rate is ∼3.6 kHz with a dead time of 4% and the average duty cycle is higher than 85%.

3 Data analysis

The ARGO-YBJ data used in this analysis were collected from 2006 July to 2011 February. The total effective observation time is 1265 days. To achieve a better angular resolution, the event selections used in [15] is applied here and only events with zenith angle less than 50 degrees are used. The total number of events after filter used in this work is 1.7×10^{11}. In order to obtain a sky map using events, the celestial coordinates (right ascension and declination) is divided into a grid of 0.1°×0.1° bins and filled with detected events according to their reconstructed origin. In order to extract an excess of γ-rays from each bin, the so-called “direct integral method” [16] is applied to estimate the number of cosmic ray background events in the bin. To remove the affection of large scale anisotropy, a correction have been applied which can be found in [15]. To take into account the PSF of the ARGO-YBJ detector, the events in a circular area centered on the bin with an angular radius of ϕ_{10} are summed together. The Li-Ma formula [17] is used to estimate the significance.

4 Results

The significance distributions from all directions with declinations from -10° to 70° are shown in Figure 1. There are significant excess points with significance greater than 5 s.d., which can be attributed to the four known VHE γ-ray sources, i.e. Crab, Mrk421, MGRO J1908+06 or MGRO J2031+41 shorter than 4 degree.

![Figure 1: The wide solid line is the distribution of significance of all directions on the northern sky map with declinations from -10° to 70°. The thin solid line represents the best Gaussian fit to the distribution of significance excluding those cells that have a distance to the Crab, Mrk421, MGRO J1908+06 or MGRO J2031+41 shorter than 4 degree.](image)

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<tr>
<td>83.75</td>
<td>22.15</td>
<td>16.9</td>
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<td>166.25</td>
<td>38.25</td>
<td>13.6</td>
<td>Mrk 421</td>
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<td>286.85</td>
<td>6.55</td>
<td>6.1</td>
<td>MGRO J1908+06</td>
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<td>307.85</td>
<td>41.95</td>
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Table 1: Location of all regions with an excess greater than 5 S.D.

Figure 2 shows the significance map of the northern sky as determined from the ARGO-YBJ data. There are four sources clearly visible in the map. Table 1 list the location of all regions with significance greater than 5 S.D.. For each independent region, only the pixel with the largest significance is presented in Table 1. The position is consistent with the ARGO-YBJ pointing error 0.2°.

Recently, the Milagro experiment observed 14 of the 34 selected Fermi sources at a pre-trial significance of 3 S.D. or more at the representative energy of 35 TeV [18]. A similar result is also obtained by the ASγ experiment [19]. As an independent experiment, ARGO-YBJ observation on
these source can provide more information. Table 2 lists the ARGO-YBJ result for the 15 candidate sources. 14 of 15 sources are observed with significance greater than 0 S.D.. 9 of 15 sources are observed with significance greater than 1.5 S.D. with expected 1. The chance probability from Poisson statistics would be estimated as $10^{-6}$. It clearly shows that these sources have statistically significant correlations with the TeV γ-ray excesses.

To estimate the energy response and the sensitivity of the ARGO-YBJ detector, we simulate different sources in the sky with different declinations. For each source we follow a complete transit that is 24 hours of observation. The simulated events are sampled in the energy range from 10 GeV to 100 TeV, then the full Monte Carlo simulation of the detector is performed. Figure 3 shows the median energy of γ-rays that trigger ARGO-YBJ and satisfy the event selections as function of source declination. Different lines indicate source with different spectral indices from -2.0 to -3.0.

Except the four sources listed in Table 1, the significance from all directions are not high enough to claim any signal, therefore, we set a 90% confidence level (C.L.) upper flux limit for all directions in the sky. To obtain a good data sample with same detector configure, only events collected with 154 clusters, that is from 2007 November to 2011 February, are used to estimate the upper limit. Firstly, the statistical method given by Helene [20] is used to calculate the upper limit on the number of signal events at 90% confidence level.
The ARGO-YBJ experiment is an air shower array with large field of view and have continuously monitored the northern sky since 2007 November. Using data up to 2011 February, we have presented the northern sky survey for the VHE $\gamma$-ray point sources in a declination band between $-10^\circ$ and $70^\circ$. There are four sources are observed with significance greater than 5 S.D.. The significance from Crab Nebula is more than 17 S.D., which indicates that this source must have a very hard energy spectrum. Details analysis could be found in [21].

5 Conclusion

The ARGO-YBJ experiment is an air shower array with large field of view and have continuously monitored the northern sky since 2007 November. Using data up to 2011 February, we have presented the northern sky survey for the VHE $\gamma$-ray point sources in a declination band between $-10^\circ$ and $70^\circ$. There are four sources are observed with significance greater than 5 S.D.. The significance from Crab Nebula is more than 17 S.D., which indicates that the cumulative sensitivity of ARGO-YBJ has reached 0.3 Crab units. The 90% C.L. upper limits of $\gamma$-ray flux on all the direction are obtained under the hypothesis of point sources with power-law spectra. The integral flux limits above 0.1 TeV vary within 0.09 and 0.53 Crab unit for Crab-like source depending on the declination of the candidate source, which is more restrictive than previous limits. While these limits are the best available to date, ARGO-YBJ is still collecting data as the only one running EAS at TeV energy band all over the world. Its cumulative sensitivity will improve with time, therefore, better limits will be obtained and some new source may be detected in the foreseeable future.

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