Observation of TeV gamma rays from the Cygnus region with the ARGO-YBJ experiment

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Abstract: MGRO J2019+37 is the most significant source in Milagro data set apart from the Crab Nebula at 20 TeV. It has not been confirmed by other observations at energy above 100 GeV. The ARGO-YBJ experiment is an air shower array with large field of view and can continuously monitor the northern sky, which is similar to the Milagro experiment. With a similar sensitivity as that of the Milagro experiments, ARGO-YBJ is the best candidate to observe MGRO J2019+37. The data sets collected from 2007 November to 2011 February are used to search for steady γ-ray emission from the Cygnus region. Except for a signal with 5.8 standard deviations from MGRO J2031+41, no evidence for statistically significant γ-ray signal from MGRO J2019+37 was found. The spectrum of MGRO J2031+41 is obtained. The flux upper limit for MGRO J2019+37 is estimated at 90% confidence level.

Keywords: MGRO J2019+37, γ-ray observation, Cygnus region, ARGO-YBJ

1 Introduction

The Cygnus region of the Galactic plane is known as the brightest diffuse γ-ray emission in the northern sky revealed by both Fermi [1] and its predecessor EGRET [2]. Complex features have been revealed in broad wavelength bands of radio, infrared, x-rays, and γ-rays. This region is rich in potential cosmic-ray acceleration sites, e.g., Wolf-Rayet stars, OB associations and supernova remnants. Recently, 17 γ-ray sources, including 6 pulsars (as listed in Table 1), 1 micro-quasar, 1 potential supernova remnant and 9 unidentified sources, were detected using Fermi LAT first year data inside the region with $65^\circ < l < 85^\circ$ and $-3^\circ < b < 3^\circ$ [1]. These sources are considered potential very high energy (VHE) γ-ray sources. The Cygnus region is, therefore, a natural laboratory for the study of cosmic ray origins.

Several VHE γ-ray sources have been detected inside the Cygnus region in the past decade. The first source is TeV J2032+4130 discovered by the HEGRA collaboration [3, 4] and has been confirmed by other collaborations, i.e. Whipple [5] and MAGIC [6]. Its extended radius is estimated to be about 0.1°. Its spectrum is hard with index about -2.0 and the integral flux is about 5% of the Crab unit at energy above 1 TeV. MGRO J2031+41, detected by the Milagro collaboration at 20 TeV [7], is spatially consistent with the source TeV J2032+4130, while the extension is larger with diameter $3.0^\circ \pm 0.9^\circ$. This source is likely related to the coincident Fermi PSR J2032+4127 [8].

The second VHE γ-ray source observed from this region is Cyg X-1 from which a γ-ray flare, coinciding with an X-ray flare, is observed by the MAGIC collaboration on September 24th 2006 [9].

The source VER J2019+407 is discovered by the VERITAS collaboration when they survey the Cygnus region [10]. Their preliminary result shows the extension of $0.16^\circ \pm 0.028^\circ$ and $0.11^\circ \pm 0.027^\circ$ along the major and minor axes, respectively. The closest Fermi source is Fermi pulsar 1FGL J2021.5+4026, while they are unlikely to be associated due to the 0.5° offset. The nature of VER J2019+407 is still unclear.

This region also contains a bright unidentified source MGRO J2019+37, which is detected by the Milagro collaboration at 20 TeV [7] and is the most significant source in Milagro data set apart from the Crab Nebula. The extension is estimated to be $0.32^\circ \pm 0.12^\circ$ [11]. The SED of this source is hard with index -1.83, which is cut off at 22.4 TeV [12]. Closed to MGRO J2019+37, a marginal signal is detected by the Tibet ASγ collaboration [13]. This source is spatially coincident with Fermi PSR J2021+3651 [8]. Recently, VERITAS has surveyed this region, yet no emission from MGRO J2019+37 has been detected [10], however, with a limited field of view (FOV), VERITAS's null detection can be plausibly interpreted as the large extension of the source.

Among the 4 known VHE γ-ray sources inside Cygnus region, MGRO J2019+37 is mysterious due to high flux while without confirmation by other VHE γ-ray detectors. To measure the energy spectrum or set an upper limit around several TeV is therefore very useful in understanding the emission mechanism. The ARGO-YBJ experiment is an air shower array with large FOV and can continuously

longitude (deg)	latitude. (deg)	Source Name
68.7655	2.8232	1FGL J1952.9+3252
65.2442	0.3765	1FGL J1954.3+2836
65.8801	-0.3540	1FGL J1958.6+2845
75.2257	0.1169	1FGL J2021.0+3651
78.2282	2.0847	1FGL J2021.5+4026
80.2240	1.0280	1FGL J2032.2+4127

Table 1: List of GeV PSR detected by Fermi inside Cygnus region.

monitor the northern sky, which is the same as the Milagro experiment does. The total exposure of the Crab Nebula achieves about 1200 days with statistical significance of 17 standard deviations (S.D.), which is comparable with the 8-year cumulative sensitivity of Milagro with 17.2 S.D. [14] but at different energy regions. The ARGO-YBJ experiment is, therefore, the best candidate to observe MGRO J2019+37. This work attempts to present the observation of TeV γ-rays from MGRO J2019+37 with the ARGO-YBJ experiment.

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 is composed of 12 RPCs) are installed to form a carpet of about 5600 m^2 with an active area of $\sim$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 $\times$ 100 m. More details about the detector and the RPC performance can be found in [15, 16]. 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 (denoted as ψ) 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 [17] has been developed using cosmic ray showers. The calibration precision is 0.4 ns and the procedure is applied every month [18].

The central 130 clusters began taking data in 2006 July, and the "guard ring" was merged into the DAQ stream in 2007 November. The trigger rate is $\sim$3.5 kHz with a dead time of 4% and the average duty cycle is higher than 86%.

3 Data analysis

The ARGO-YBJ data used in this analysis were collected from 2007 November to 2011 February. The total effective observation time is 1024 days. To achieve a better angular resolution, the event selections used in [19] is applied here and only events with zenith angle less than 50° are used. The total number of events after being filtered used in this work is 1.7×10^{11}. In order to obtain a sky map using events, an area centered at the source location in celestial coordinates (right ascension and declination) is divided into a grid of $0.1^\circ \times 0.1^\circ$ bins and filled with detected events according to their reconstructed origin. In order to extract an excess of γ-rays from the source, the so-called "direct integral method" [20] is adopted to estimate the number of cosmic ray background events in the bin. To remove the affection of cosmic ray anisotropy, a correction has been applied which can be found in [19]. Taking into account the PSF of the ARGO-YBJ detector, the events in a circular area centered on the bin with an angular radius of 2ψ are summed together using a technique of Gaussian smoothing. The Li-Ma formula [23] is used to estimate the significance.

4 Results and discussion

Using the same data and the same analysis method, a γ-ray survey of the northern sky has be performed [21]. Four known VHE γ-ray sources are detected, i.e. Crab Nebula, Mrk 421, MGRO J1908+06, and MGRO J2031+41. The significance from Crab Nebula is more than 16 S.D., which indicates that the cumulative sensitivity of ARGO-YBJ has reached 0.3 Crab units. MGRO J1908+06 is the second significant source among three extent sources discovered by the Milagro collaboration. This source has been confirmed by the H.E.S.S. collaboration [22]. According to the further analysis using ARGO-YBJ data, the extension is $0.50^\circ \pm 0.35^\circ$ [25], which is consistent with the H.E.S.S. measurement 0.34°. The measured spectrum is in good agreement with Milagro, while they are much larger than the spectrum determined by H.E.S.S.. MGRO J2031+41 is the third significant source discovered by the Milagro collaboration locating inside the Cygnus region, which has been introduced in Section 1. It is interesting that the most significant source in Milagro data set MGRO J2019+37 is not detected using the ARGO-YBJ data. This source also locates inside the Cygnus region.

Figure 1 shows the significance map of the Galactic plane containing the Cygnus region for the ARGO-YBJ data. The Cygnus region is systematic excess with a large region, which indicates the possible diffuse γ-ray emission. Further analysis about the diffuse γ-ray emission using ARGO-YBJ data can be found in [24]. The highest significance value is 5.8 S.D. locating at (307.8°,41.9°), consistent with the location of VHE sources MGRO J2031+41 and TeV J2032+4130.

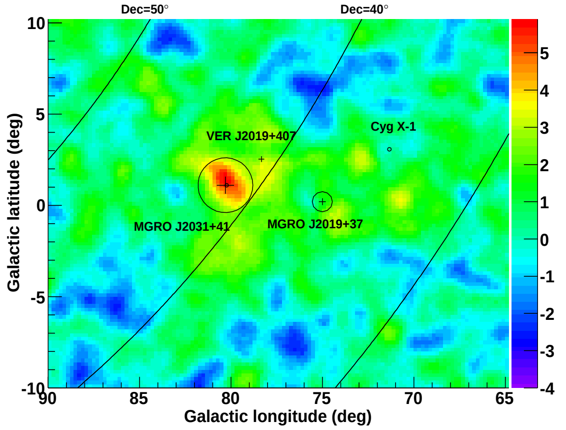

Figure 1: Significance map of the Cygnus Region Sky observed by the ARGO-YBJ experiment. The four known VHE γ-ray source are marked. The errors of the sources' position are marked with plus, i.e. MGROJ2019+37, MGROJ2031+41, while the circles indicate their intrinsic extent size [7, 11]. The plus for VER J2019+407 indicates the extension [10]. The source of Cyg X-1 is marked with circle without position error. The circle within errors of MGROJ2031+41 indicate the position and the extension of source TeV J2032+4130 estimated by the MAGIC collaboration [6].

4.1 MGRO J2031+41

To estimate the intrinsic extension of source MGRO J2031+41, only events with $N_{pad} > 60$ are used. In simulation, the source extension varies from 0° to 1° with a step of 0.1°, and the least square method is used to search the best fit to data. Figure 2 shows the distribution of θ^2-value for excess events and the best fit in simulation, where θ is the space angle to the position of TeV J2032+4130. The intrinsic extension is determined to be $\sigma_{ext} = (0.2^{+0.4}_{-0.2})°$, consistent with the estimation by the MAGIC and HERGRA collaborations 0.1°. Assuming its intrinsic extension $\sigma_{ext} = 0.1°$, we estimate its SED using the same method as that in [19] based on ARGO-YBJ data. The ARGO-YBJ detector response is taken into account. The simulated events are sampled in the energy range from 10 GeV to 100 TeV. The SED can be fitted by a power-law function as shown in Figure 2. The differential flux (TeV^{-1} cm^{-2} s^{-1}) within energy range from about 0.6 TeV to 7 TeV is

$$\frac{dN}{dEdAdt} = (1.40 \pm 0.34) \times 10^{-11} (\frac{E}{1TeV})^{-2.8 \pm 0.4} \quad (1)$$

which is 10 and 17 times higher than the flux of TeV J2032+4130 determined by the HEGRA and MAGIC collaborations, respectively, at energy above 1 TeV. The flux reported by Milagro at 20 TeV is also much higher than the naive extrapolation of the SED of TeV J2032+4130, which is clearly shown in Figure 3. Besides the statistic error shown in Eq(1), the systematic error is estimated to

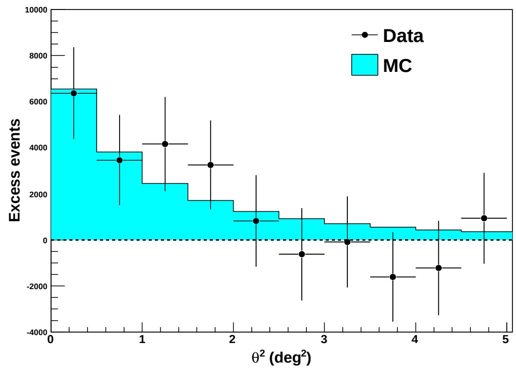

Figure 2: Distribution of θ^2 for number of excess events. The filled region is the best fit to data in simulation.

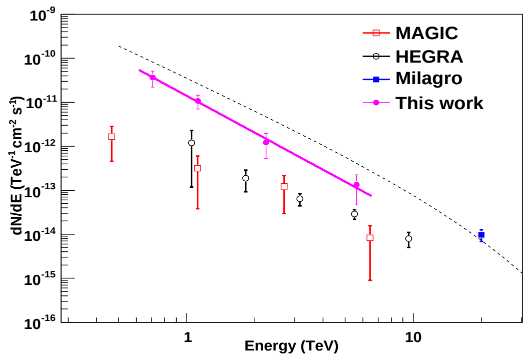

Figure 3: Differential energy spectrum from TeV J2032+4130 or MGRO J2031+41 as measured by the ARGO-YBJ experiment in pink solid line. The spectral measurements of HEGRA [4], MAGIC [6] and Milagro [12] are also marked for comparison. The dashed line indicates the SED of Crab Nebula.

be less than 30% in the flux level determination. To estimate the contribution from the diffuse emission, a region surrounding the source with space angle within the range of 3°-5° is used. The contribution in flux is about 25%, which is energy dependent and the contribution at lower energy is higher, subsequently, the spectral index seems softer.

4.2 MGRO J2019+37

Except the only one detection of MGRO J2031+41 inside the Cygnus region, no excess above 3 S.D. from MGRO J2019+37 is detected. With the second and third significant sources in Milagro data set, i.e., MGRO J1908+06 [25] and MGRO J2031+41, having been detected by the ARGO-YBJ experiment, it is interesting with null detection from the first significant source MGRO J2019+37. Taking into account the position uncertainty reported by Milagro, the pixel with the maximum significance within 0.3° around

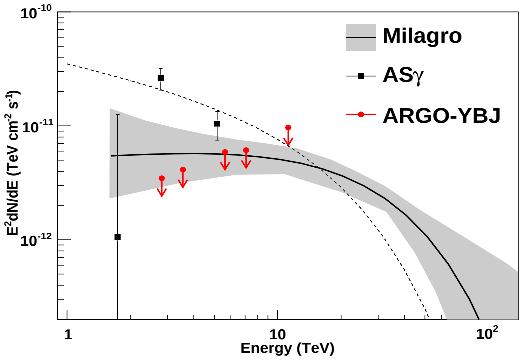

Figure 4: Upper limits on flux from MGRO J2019+37 derived by the ARGO-YBJ experiment with assuming the SED [12]. The intrinsic extension is assumed to be $\sigma = 0.32°$. The solid line and shadow indicate the differential energy spectrum and 1 sigma error region as determined by the Milagro experiment [12]. The square points are the flux determined by the ASγ experiment [13]. The dashed line indicates the SED of Crab Nebula.

the source is used to estimate the upper limits. The flux upper limits with 90% confidence level (c.l.) are shown in Figure 4 assuming the SED reported in [12] and the intrinsic extension $\sigma = 0.32°$ published in [11]. For comparison, the SED reported by ASγ [13], estimated according to a signal with a pre-trial significance of 5.8 S.D., is also marked in Figure 4, which is higher than the flux reported by Milagro and much higher than the upper limits derived in this work. The upper limits at energy around 3 TeV are lower than the Milagro flux, which indicates that its flux may be not stable.

Taking into account the source with extension $\sigma = 0.32° \pm 0.12°$ and the Cygnus region at a distance of $1-2$ kpc, the source radius is estimated $4-15$ pc, implying that the variation time scale should be longer than $13-49$ years. The observation time performed in this work is about 5 years later than that of Milagro observation on averaged, therefore, the flux variation from the whole extended region can not be completely excluded. However, a reasonable possibility is that the source have a complex structure and the variation originates from a smaller region.

5 Conclusion

The ARGO-YBJ experiment is an air shower array with large field of view and has been continuously monitoring the northern sky since 2007 November. Using data up to 2011 February, we have presented its observation result on the Cygnus region, inside which two bright very high energy γ-rays sources with extension have been detected by the Milagro collaboration. A signal consistent with MGRO J2031+41 is detected with 5.8 S.D. by the ARGO-YBJ experiment. The position and extension size are consistent with TeV J2032+4130, however, the flux is at least 10 times higher than that of TeV J2032+4130. No signal from MGRO J2019+37 is detected. The derived upper limits with 90% confidence level are lower than the Milagro flux at energy below 3 TeV, which indicates that its flux may be not stable. In conclusion, the Cygnus region is found of a complex feature at very high energy band and no firm results are drawn up to now. Hence, further observations performed by a instrument with better angular resolution, large FOV and better sensitivity are encouraged to achieve a firm conclusion on the SED and morphology of the sources.

6 acknowledgments

This work is supported in China by NSFC (No.10120130794), the Chinese Ministry of Science and Technology, the Chinese Academy of Sciences, the Key Laboratory of Particle Astrophysics, CAS, and in Italy by the Istituto Nazionale di Fisica Nucleare (INFN).

We also acknowledge the essential supports of W.Y. Chen, G. Yang, X.F. Yuan, C.Y. Zhao, R. Assiro, B. Biondo, S. Bricola, F. Budano, A. Corvaglia, B. D'Aquino, R. Esposito, A. Innocente, A. Mangano, E. Pastori, C. Pinto, E. Reali, F. Taurino and A. Zerbini, in the installation, debugging and maintenance of the detector.

References

[1] Abdo, A. A. et al. 2010, ApJS, 188, 405
[2] Hunter, S. D., et al. 1997, ApJ, 481, 205
[3] Aharonian, F., et al. 2002, A&A, 393, L37
[4] Aharonian, F., et al. 2005, A&A, 431, 197
[5] Konopelko, A., et al. 2007, ApJ, 658,1062
[6] Albert, J., et al. 2008, ApJ, 675, L25
[7] Abdo, A. A., et el. 2007, ApJ, 664, L91
[8] Abdo, A. A. et al. 2010, ApJS, 187, 460
[9] Albert, J., et al. 2006, ApJ, 665, L51
[10] Weinstein, A. 2009, arXiv:0912.4492v1
[11] Abdo, A. A., et el. 2007, ApJ, 658, L33
[12] Smith, A.J. 2009, arXiv:1001.3695v1
[13] Wang, Y. 2007, 30^{th}ICRC, Mexico, 2, 695
[14] Abdo, A. A., et el. 2009, ApJ, 700, L127
[15] Aielli, G., et al. 2006, Nucl. Instrum. Meth. A, 562, 92
[16] Aielli, G., et al. 2009, Nucl. Instrum. Meth. A, 608, 246
[17] He, H.H., et al., 2007, Astropart. Phys., 27, 528
[18] Aielli, G., et al. 2009a, Astrop. Phys., 30, 287
[19] Bartoli. B., et al. 2011, ApJ, 734, 110
[20] Fleysher, R., et al. 2004, ApJ, 603, 355
[21] Cao, Z., Chen, S.Z. 2011, 32^{th}ICRC
[22] Aharonian, F., et al. 2009, A&A, 499, 723
[23] Li, T.P.,& Ma, Y.Q. 1983, ApJ, 272, 317
[24] Ma, L.L., 2011, 32^{th}ICRC
[25] Vernetto, S., 2011, 32^{th}ICRC