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Search for very high energy gamma rays from possible ultra-high energy cosmic ray sources by the MAGIC Telescope

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Abstract: The origin of ultra-high energy (UHE) cosmic rays is still an open question. In the present work, we searched the possible UHE cosmic ray sources using the MAGIC telescope for the associated very high energy (VHE) gamma ray emission. Due to constrained propagation distance of such cosmic rays, we selected nearby galaxies in vicinity of the direction of the AGASA triplet and a HiRes UHE cosmic ray event: NGC3610 and NGC3613 (quasar remnants); Arp299 (a system of colliding galaxies). No significant excess in the VHE region was found found from these objects or their surrounding region. At multi-100 GeV regime, the upper limits on fluxes were given against gamma ray sources in surrounding region. The presented limits constrain the flux of a new hypothetical source in the region, provided the cosmic rays are emitted from a single point-like origin.

Introduction

Cosmic rays up to an $\sim 3 \times 10^{20}$ eV energy have been observed so far, while their origin remains unidentified. In the standard particle acceleration models, possible candidates are only a few types of the most powerful or very large-scale objects. Due to the lack of data on Galactic and extragalactic magnetic fields, it is difficult to trace back to their sources. However, the AGASA group claimed that a part of UHE cosmic ray events cluster in their arrival direction distribution ([1] and references therein). Several groups have also pointed out a notable angular correlation with particular class of objects such as BL Lacertae objects, which include known VHE gamma ray emitters [2]. A similar correlation was reported on quasar remnants [3]. By the quasar remnant scenario [4], the rotational energy of the black hole is dominantly radiated in MeV–TeV band whose luminosity can be a few orders higher than that of cosmic rays. If quasar remnants within several tens of Mpc are the origin of all observed cosmic rays above 10^{20} eV, they would overshine more than any known TeV gamma ray source. But in the case that hundreds of such sources distribute over several 100 Mpc space, the cosmic ray flux, at least around sev-eral 10^{19} eV, is consistent with flux limits by VHE gamma ray observations.

Observation

To find an evidence or hint of the UHE cosmic ray source, especially of the clustering events, we searched possible sources for VHE gamma rays with MAGIC (Major Atmospheric Gamma ray Imaging Cherenkov) Telescope [5]. The detector consists of the world's largest 17-m-diameter reflector viewed by photo-multiplier tube camera with $3.5°$ field of view (FOV). It is located at the Observatorio del Roque de los Muchachos (2200 m above sea level), La Palma, Canary Islands.

Table 1 summarises the UHE cosmic ray cluster (AGSAA triplet) in the Plough, Ursa Major where with AGASA data alone three events above 4×10^{19} eV had been observed in a $2.5°$ radius. Recently, the HiRes group detected a 3.7×10^{19} eV near the triplet and estimated the chance probability of observing such 'quartet' to be 0.6% [6]. This direction coincides in the supergalactic plane.

Along the direction of interest, we selected nearby objects that are capable sources of UHE cosmic ray observed on the Earth. To carry out delegated ob-

Dataset	$E_0^{(CR)}$	R.A.	Decl.	$\delta\theta$
AGASA	77.6	11h14m	$+57.6°$	$1.0°$
AGASA	55.0	11h29m	$+57.1°$	$1.7°$
AGASA	53.5	11h13m	$+56.0°$	$1.9°$
HiRes	37.6	11h16m	$+55.85°$	$0.4°$

Table 1: UHE events in the cluster. E_0 is the estimated energy by each experiment in 10^{18} eV (EeV). $\delta\theta$ is a nominal direction error at a 68%CL.

Object	R.A.	Decl.	m_V	D
NGC3610	11h18m4	$+58°47'0$	8.5	31
NGC3613	11h18m6	$+58°00'6$	8.9	34
Arp299	11h28m5	$+58°33'9$	11.8	37

Table 2: Locations of the observed objects in the present work. m_V is visible magnitude. D is distance in Mpc ($H_0 \sim 70$ [km h^{-1} Mpc^{-1}]).

servations, we picked out the following three objects as summarised in Table 2.

NGC3610 is a merger remnant elliptical galaxy with a black hole of $\sim 0.5 \times 10^8$ solar masses $M_\odot$. The maximum accessible cosmic ray energy is estimated to be 4.4×10^{19} eV. This galaxy has attracted attentions because of its fine structure and prominently warped disk, implying that a dynamical event occurred in a few 10^9 years ago [7].

NGC3613 is a quasar remnant with a black hole of $1.6 \times 10^8 M_\odot$. The maximum cosmic ray energy is estimated to be 5.9×10^{19} eV. This galaxy is located $0.7°$ off the most energetic triplet event.

Arp299 (Mrk 171, VV118; [8] and references therein) is a starburst galaxy and a system of colliding galaxies (NGC3690+IC694). It is characterised by an extreme star formation rate. The supernova rate is also as high as ~ 0.5 per year. Arp299 is pointed out to be a potential source to explain the AGASA triplet [9].

Operating the MAGIC telescope, we observed NGC3610 for 5.1 hours, NGC3613 for 5.0 hours each in December 2006 and Arp299 for 9.9 hours in January 2007. All the observations were carried out by the so-called wobble mode [10] in which the object position was tracked alternatively $0.4°$ east or west off the centre of FOV.

Analysis and result

The data analysis was performed by our standard analysis chain MARS (MAGIC Analysis and Reconstruction Software) [11]. The image of observed showers was parameterised by the conventional Hillas technique [12]. To interpret data, a number of simulated air showers were generated under actual telescope configurations [13]. For rejection of the background hadronic shower events, we used the random forest (RF) method [14]. To define the parameter 'hadronness' H that represents how hadron-like showers look (=0 for gamma ray- and =1 for hadron- like), the RF algorithm is trained with data and simulated gamma ray shower samples for compatible zenith angles ($29° - 45°$). The energy of primary gamma rays was estimated similarly by the RF with simulated gamma ray showers. The energy resolution is $< 25\%$ at energies of interest. The incoming direction of showers was reconstructed by the so-called DISP method [15]. The typical angular resolution is $\sim 0.1°$.

First we search for the VHE gamma ray emission directly from the observed object. To select gamma ray like showers, the criterion of H cut was optimised by simulated gamma ray showers by maximizing their significance against surviving background events. θ^2 distribution is compared with that of OFF-sources (expected background distribution) where θ is the angular distance between reconstructed shower incoming direction and the object position. The cut for θ^2, typically ~ 0.02 [degree^2], was similarly optimised by simulated showers and was applied on the data.

Figure 1 shows an example of θ^2 distribution on Arp299 ($E_{est} \geq 200$ [GeV]) in which no significant excess was found for gamma ray signals.

Also for other objects, no significant excesses was found. Therefore the upper limits of gamma ray fluxes were estimated for these cases. In four estimated energy bins, the acceptance of gamma ray showers after cuts were evaluated by the simulated samples independent of ones used in the RF.

The limits on the fluxes at a 95% confidence level (CL) are summarised in Table 3. The integral flux limits above ≥ 200 GeV correspond to $\sim 7\%$ for NGC 3610 and NGC 3613 and 5% for Arp 299 to the Crab flux observed by MAGIC [16].
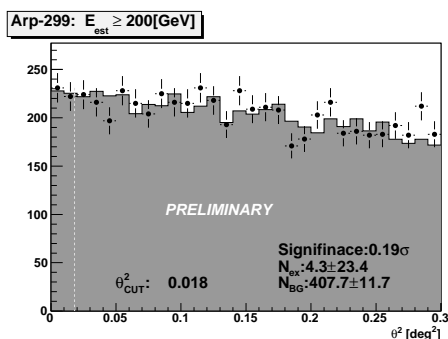
Figure 1: An example of θ^2 distribution (Arp299; $E_{\mathrm{est}} \geq 200[\mathrm{GeV}]$) . Closed circles: ON-source Histogram: OFF-source data, respectively. The vertical line: optimised cut of θ^2 for this case

$\langle E_0 \rangle$	UL [10^{-14} cm^{-2} s^{-1} GeV^{-1}]		
[GeV]	NGC3610	NGC3613	Arp299
216	18.	16.	12.
463	2.5	2.3	1.7
921	0.61	0.60	0.43
1266	0.32	0.30	0.24

Table 3: Upper limits on gamma ray fluxes from observed objects at a 95% CL.

To search for any emission apart from the thse objects, the significance of the excess events by Equation (17) in [17] was estimated for each sky point using the cumulative dataset. The background distribution was modelled by the data observed on the non-source region at similar zenith angles.

Figure 2 shows the significance map for $E_{\mathrm{est}} \geq 300$ GeV with a convolution of the angular resolution. Crosses denote positions of objects. Stars represent two AGASA events. The solid curve is a $1°$ circle centred on the cicumcentre of three objects to accomodate to a moderately flat sensitivity. Figure 3 shows the significance distribution for $0.1° \times 0.1°$ bins within this circle. The distribution is compatible with non-source hypothesis.

Concluding remarks

Following up with AGASA-HiRes quartet detection, we searched the possible UHE cosmic ray
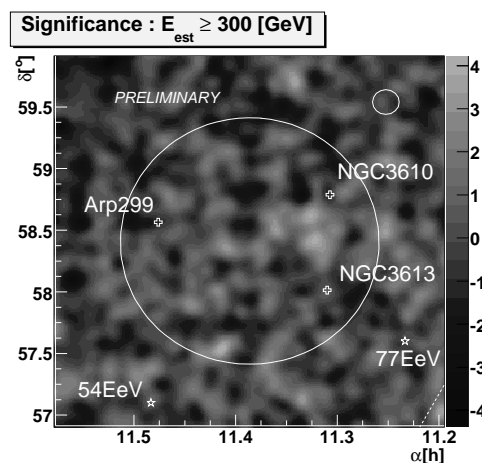

Figure 2: Significance map ($E_{\mathrm{est}} \geq 300[\mathrm{GeV}]$) of the observed region smoothed by the angular resolution. $\sim 0.1°$. Crosses: positions of objects. Stars: AGASA events. The solid curve: $1°$ circle from the cicumcentre of observed objects.
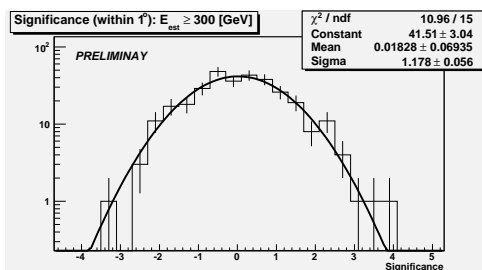

Figure 3: The significance distribution within solid curves ($1°$ radius) in the map of Figure 2.

sources, nearby quasar remnants NGC3610 and NGC3613 and a starburst galaxy Arp299, for VHE emission. In $\sim 200 - 500$ GeV energies, the upper limits on the gamma ray flux from each source is placed against each object and were $\sim 8\% - 12\%$ Crab flux at a 95% CL.

Over the region observed, there are no positive signals for the VHE emission by effectively ~ 15 hour observation. Assuming the triplet is a UHE cosmic ray signal from a single source, its energy flux yields ~ 2 eV cm^{-2} s^{-1} by the AGASA observation. If any of the observed objects is a responsible cosmic ray source, the present limits cor-

respond to $\sim 3-5$ times of the energy flux of UHE cosmic ray component.

In near future, if nearby sources exist, UHE cosmic ray clusters will be found even clearly by higher quality data provided by > 1000-km^2-scale observatories. With progress of imaging Cherenkov telescopes as well, it is highly expected to identify the sources by both ways of cosmic rays physics and gamma ray astronomy to approach the the mystery of UHE cosmic ray origin.

Acknowledgment

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