Search for TeV Gamma-Rays around the merger cluster Abell 3376 with CANGAROO-III

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***Abstract*. The CANGAROO-III Imaging Atmospheric Cherenkov Telescopes observed the nearby (z=0.046) rich cluster of galaxy Abell 3376 during the period from Nov in 2007 to Jan in 2008. In the peripheral cluster regions the Mpc-scale ringlike radio relics are found by Very Large Array telescope observations. This structure may be associated with cosmological shock waves, which are thought as an acceleration site for ultra-high-energy cosmic rays. We search for TeV gamma-ray emissions around the cluster and compare the observational result with non-thermal emission models.**

***Keywords*: gamma-ray, cluster of galaxies, Abell 3376**

I. Introduction

The cosmic rays are expected to be produced efficiently by the first order Fermi acceleration at the shock waves. In the Universe there exist various size shock waves, range in scale over 15 orders of magnitude from the size of the earth's bow shock $\sim$ 10km up to the size of intergalactic shock waves $\sim$Mpc [1]. The cosmic rays above 10^{19}eV are believed to be of extragalactic origin, since a proton with energy of 10^{19}eV in a typical galactic magnetic field 1μG has a gyroradius of 10kpc. The possible shock acceleration sites are gamma-ray bursts, active galactic nuclei, radio galaxy lobes, galactic wind, and/or cluster of galaxies. Among the candidates the cosmic-ray protons accelerated in cluster of galaxies are stored in the Hubble time. Nearby rich clusters [2] and merger of clusters [3] are promising sources of steady extended gamma-ray emissions due to neutral pion decay.

The merger events are understood to be as a result of the hierarchical clustering of cosmic structure formation. The total budget of energy is $\sim 10^{63}$ ergs, which is yielded by the clusters with the mass $10^{14} M_{\odot}$ colliding at the velocity 10^3 km s^{-1}. This phenomena provide the energy not only for cosmic-ray protons but also for cosmic-ray electrons. The resulting non-thermal emissions should appear in the radio and X-ray bands besides gamma-ray. Of special interest is the case where extended double radio relics are located at the periphery of a cluster and are symmetric around the cluster center.

The radio relics are generally thought to be the signature of ongoing mergers [4]: cosmological merging shocks may accelerate electrons, which produce diffuse radio synchrotron emissions.

So far only a small number of clusters with double relics were found. For instance, Abell 3667 (the redshift of z=0.055) has strong polarized double relics, which are located symmetrically and perpendicular to the elongated thermal X-ray emission axis [5]. Recent Very Large Array telescope observations have discovered a few clusters in this category [6], [4]. One of them is the nearby (the redshift of z=0.046) rich cluster of galaxy Abell 3376 with the Mpc-scale double relics. Since there is no optical galaxy associated with the relics, these structures are not usual radio galaxies and are interpreted as outgoing merger shock waves [6]. Suzaku observations gave upper limits of the non-thermal hard X-ray emissions on the center with the eastern radio relic and the peripheral region with the western [7].

To explorer non-thermal emissions at high energy end of the radio relics, the search for diffuse TeV gamma-ray emissions is necessary. This is the second search of CANGAROO-III for the clusters with double relics after Abell 3667 [8]. These Mpc-scale radio relics are located within the apparent radius of 0.5° from the center. These search are suitable for Imaging Atmospheric Cherenkov Telescopes, since the gamma-ray acceptance does not decrease significantly within the radius.

II. Observation of Abell 3376

We observed the cluster of galaxies Abell 3376 with CANGAROO-III telescope during the period from Nov 30 to Dec 17 in 2007 and from Dec 29 in 2007 to Jan 6 in 2008. We use "wobble mode" [9] in which the pointing position of each telescope was shifted in declination between ±0.5 degree from the center of the tracking position every 20 minutes. Each night the data were taken for two observation runs: ON-source runs and OFF-source runs. During the ON-source runs, the center of the field of view of each telescope was set at (RA, Dec)=(90.4°, -40.0°) [J2000], which is the center of the ellipse obtained by an elliptical fit to the peripheral radio relic structures [6]. The ON-source runs were timed to contain the meridian passage of the target. On the average, the OFF source regions were located with an offset in the R.A. of about ±30° away from the target. The OFF-source runs almost have the same distribution of zenith angles with that of the ON-source runs. The total observation times are 1237 and 1069 min, for ON and OFF sources runs, respectively.

We also observed dark regions without bright stars every month in order to estimate the light collecting efficiencies, including the reflectivity of the segmented mirrors, the light guides, and the quantum efficiency of the photomultiplier tubes. We analyzed the local muon-ring events [10] to monitor the total performance of the telescopes. The ratios of the light yield per unit arc-length at the observation periods to those at the mirror production time can be estimated. Since the Abell 3376 was observed across two observation periods, we used the average values for T3 and T4. However, we assume the value measured at Sep in 2007 for T2, because the value of T2 at the end of 2007 contains large error due to the low mirror reflectivity. As a result, we used 0.47, 0.53, and 0.47, for the value of T2, T3, and T4, respectively.

III. Data Analysis Procedures

First we selected the shower events with the images of the Cherenkov light in all three telescopes, images which have at least 5 adjacent camera pixels above 5 photoelectrons threshold and within ±30 nsec from the average arrival time of all hit pixels. And we discarded events with hit pixels at the outermost edge of the cameras. Finally we reject the data during low trigger-rate periods under the 4 Hz condition. The effective observation times are 972 and 827 min, for ON and OFF sources runs, respectively. The averages of the zenith angle of the data used for the analysis were 12.5° and 12.7°, respectively.

Next we calculated Hillas parameters for the images of three telescopes. The shower arrival directions were reconstructed by minimizing the sum of squared widths of the three images seen from the assumed position. We calculated the Fisher Discriminant (hereafter FD) [11], to apply as a measure of gamma-ray/hadron separation. The FD is defined as a linear combination of the image parameters, which are energy-corrected $widths$ and $lengths$ for the T2, T3, and T4.

The FD distribution FD_{bg} of background hadron events can be obtained from the OFF-source data and that FD_γ of gamma-ray events form Monte Carlo simulation data. By fitting the FD distributions FD_{on} of the ON-source data with a linear combination of FD_γ and FD_{bg}, we determine the number of gamma-ray excess events in the ON-source regions. The details of these analysis procedures are explained in [10].

Here, in order to search for diffuse gamma-ray emissions in the peripheral cluster regions with the Mpc-scale ringlike radio relics, gamma-ray Monte Carlo simulations were performed on the assumption of a power-law spectrum index -2.1 and the extended radius of 0.5°. The light collection efficiency estimated from muon-ring events and the spot size of each telescopes were taken into account on these simulations.

IV. Results

In order to search for a gamma-ray excess around the cluster Abell 3376, we produced the FD distribution within $\theta^2 < 0.25$ degree^2 =(0.5 degree)^2 and fitted it with the following functions: the background function was made from the FD distribution in the same region of OFF-source runs and the gamma-ray response function was made from that of the Monte Carlo simulation. The fitting parameter is the ratio of gamma-rays to total number of events. Fig. 1 shows the fitting results.

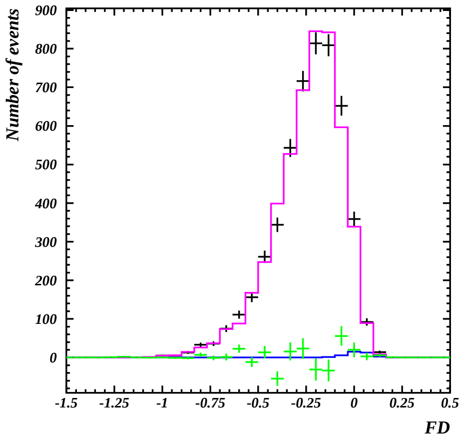

Fig. 1. Fisher Discriminant (FD) distribution for the region inside $\theta^2 < 0.25$ degree^2. The black points with error bars are obtained from the above region of the ON source runs, the red histogram is from the same region of OFF source run, the green points with error bars are subtracted data using the results of the fit, that is, "gamma-ray-like" excess events, and the blue histogram are the best-fitted gamma-ray response function obtained from Monte Carlo simulations.

FD distributions in various θ^2 slices were made. The same fitting procedure described above was carried out. We used the gamma-ray response function within $\theta^2 < 0.2$. The fitted results are shown in Fig. 2. The best-fitted excess entry was 38 $\pm$ 23 events within $\theta^2 < 0.25$. In this region, we did not find any significant signals. The threshold energy of this analysis is estimated to be $\sim$820 GeV from the Monte Carlo simulation. The preliminary 2σ integral flux upper limit above 820 GeV is 2.1×10^{-11} cm^{-2} s^{-1}.

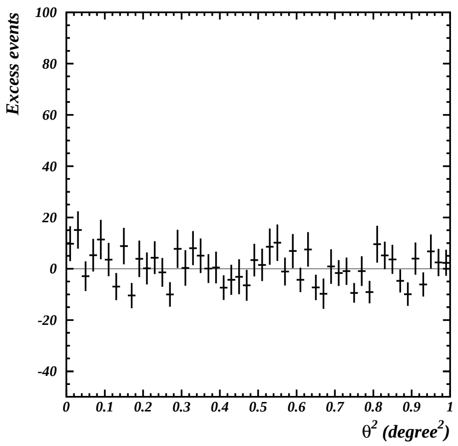

Fig. 2. The "gamma-ray-like" events distribution versus θ^2 in the unit of degree^2. The center of the peripheral radio structures in Abell 3376 is located at θ^2=0.

V. Discussion and Conclusion

To set a better upper limit, two-fold coincidence data analysis should be required. Here, using the preliminary upper limit obtained above, we discuss the total energy W_p of cosmic-ray protons. We assume that the total number spectrum of protons is proportional to the power law with an exponential cutoff $E^{-p}\exp(-E/E_{max})$ and the neutral pion decay gamma-ray emissions are dominant. The normalization factor of the proton spectrum can be determined and the gamma-ray fluxes can be calculated [12] on the assumption of the power-law index p and the cutoff energy E_{max}. Given the parameters of the p, and E_{max}, the upper limits of the total energy W_p of protons are obtained as a function of the distance d of the observed target and the number density n of the ambient matter from the observed flux upper limit. In the case of $p = 2.1$ and $E_{max} = 10^{15}$ eV, we obtain $W_p < 8.0 \times 10^{62}(d/197\mathrm{Mpc})^2(n/0.01\mathrm{cm}^{-3})^{-1}$ ergs. This upper limit is comparable to the kinetic energy of the merging clusters $\frac{1}{2}(M/10^{14}M_{\odot})(V/10^3\mathrm{km/s})^2 \sim 10^{63})$ ergs, where M is the mass of a typical cluster and V is an infall velocity merging cluster. Nearby merging clusters of galaxies should be observed further with better sensitivity.

Acknowledgments

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