Observation of clusters of galaxies with the CANGAROO-III telescope system

R. KIUCHI[1], M. MORI[1], G. BICKNELL[2], R. CLAY[3], P. EDWARDS[4], R. ENOMOTO[1], S. GUNJI[5], S. HARA[6], T. HARA[7], T. HATTORI[8], S. HAYASHI[9], Y. HIGASHI[10] Y. HIRAI[11], K. INOUE[5], C. ITOH[6], S. KABUKI[10], F. KAJINO[9], H. KATAGIRI[12], A. KAWACHI[8], T. KIFUNE[1], H. KUBO[10], J. KUSHIDA[8], Y. MATSUBARA[13], T. MIZUKAMI[10], Y. MIZUMOTO[14], R. MIZUNIWA[8], H. MURAISHI[15], Y. MURAKI[9], T. NAITO[7], T. NAKAMORI[10], S. NAKANO[10], D. NISHIDA[10], K. NISHIJIMA[8], M. OHISHI[1], Y. SAKAMOTO[8], A. SEKI[8], V. STAMATESCU[3], T. SUZUKI[11], D. SWABY[3], T. TANIMORI[10] G. THORNTON[3], F. TOKANAI[5], K. TSUCHIYA[8], S. WATANABE[8], Y. YAMADA[9], E. YAMAZAKI[8], S. YANAGITA[11], T. YOSHIDA[11], T. YOSHIKOSHI[1], AND Y. YUKAWA[1]

[1] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, 277-8582, Japan*
[2] *Research School of Astronomy and Astrophysics, Australian National University, ACT 2611, Australia*
[3] *School of Chemistry and Physics, University of Adelaide, SA 5005, Australia*
[4] *Narrabri Observatory of the Australia Telescope National Facility, CSIRO, NSW 1710, Australia*
[5] *Department of Physics, Yamagata University, Yamagata, 990-8560, Japan*
[6] *Ibaraki Prefectural University of Health Sciences, Sagamihara, 228-8555, Japan*
[7] *Faculty of Management Information, Yamanashi Gakuin University, Kofu, 400-8575, Japan*
[8] *Department of Physics, Tokai University, Hiratsuka, 259-1292, Japan*
[9] *Department of Physics, Konan University, Kobe, 658-8501, Japan*
[10] *Department of Physics, Kyoto University, Kyoto, 606-8502, Japan*
[11] *Faculty of Science, Ibaraki University, Mito, 310-8512, Japan*
[12] *Department of Physical Science, Hiroshima University, Higashihiroshima, 739-8526, Japan*
[13] *Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya, 464-8601, Japan*
[14] *National Astronomical Observatory of Japan, Mitaka, 181-8588, Japan*
[15] *Faculty of Medical Engineering and Technology, Kitasato University, Sagamihara, 228-8555, Japan*
E-mail: kiuchi@icrr.u-tokyo.ac.jp

Abstract: More than forty gamma-ray sources have been detected by atmospheric Cherenkov telescopes at TeV energies. Although there are many theoretical predictions on the possible gamma-ray fluxes from these gigantic objects assuming various emission mechanisms, no cluster of galaxies have been proven to be a TeV gamma-ray emitter until now. We have observed a couple of clusters of galaxies in the southern sky with the CANGAROO-III atmospheric Cherenkov telescope system in 2006, and preliminary results on the analysis to search for gamma-ray signature are reported.

Introduction

Observations of clusters of galaxies at various wavelength (i.e. radio, optical, X-ray, and etc.) suggest the existence of non-thermal particles in these gigantic objects [7]. In the gamma-ray band, no observational evidence has been reported from clusters of galaxies [15] (but, there could be a hint: see, for example, refs.[18, 13, 17]). If a gamma-ray flux is observed from clusters of galaxies, it would be a direct measurement of the energy density of non-thermal particles. In the past, observations in the TeV-band with atmospheric imaging telescopes yielded only upper limits [8, 2].

Recently, Inoue et al. [12] discussed the following mechanism of gamma-ray emission from Coma-like clusters of galaxies: protons could be accelerated up to $10^{18} \sim 10^{19}$ eV in the cluster accretion shocks, and secondary electron-positron pairs would be produced in the p-γ interaction with the cosmic microwave background photons, and then the electron-positron pairs could boost up those photons into the TeV range by the inverse Compton process. The predicted gamma-ray flux could be at the detectable level, depending on mainly the strength of magnetic field in the cluster of galaxies.

Here we report preliminary results from our observations of a few clusters of galaxies at TeV energies with CANGAROO-III, an array of imaging atmospheric Cherenkov telescopes. We have selected targets whose characteritics are similar to that of the Coma cluster from the southern Abell catalog [1]: Abell 4038, formerly known as Klemola 44, is a rich southern cluster with $z = 0.028$ centered at $(\alpha, \delta) = (23^h47^m45.1^s, -28°08'26")$ (J2000) [5]. Abel 3667 is a one of the brightest X-ray sources in the southern sky, and is also known to show huge diffuse radio emission around the cluster [16]. The location of its center is $(\alpha, \delta) = (20^h12^m27.4^s, -56°49'36")$ (J2000), and its refshift is $z = 0.055$ [14]. Since the radio relics around Abell 3667 might be a site of particle aceralation [14], it could be a good TeV gamma-ray candidate, however, the distance is a little farther than Coma cluster ($z = 0.023$).

Observation

We observed cluster of galaxies, Abell 4038 and Abell 3667, with the CANGAROO-III telescopes [4] in 2006. Three telescopes (we call them as $\mathrm{T2, T3, T4}$) were used for these observations and the data were recorded when any two telescopes were triggerd [3]. The observation of each cluster consists of ON-source runs and OFF-source runs: for each run we adopted *wobble* mode in which the pointing direction was shifted in declination $\pm 0.5°$ from the tracking position every 20 minutes. The total observation time are $\sim$25 hours (ON) and $\sim$24 hours (OFF) for Abell 4038 and $\sim$32 hours (ON) and $\sim$29 hours (OFF) for Abell 3667.

Analysis

We basically followed analysis procedure explained in detail in [6], so here we give a brief description.

First, we selected shower events from the data by applying clustering cuts, and we calculated the image moments(Width, Length) [11]. The typical shower rate is $\sim$7Hz, and we cut the data when the shower rate was lower than 5Hz. The effective observation time for ON and OFF source after this selection is 18.7hours and 17.7 hours for Abell 4038, and 28.7 hours and 23.7 hours for Abell 3667. After this shower image selection for each telescope, we selected only three-fold coincident events and also require that none of the each shower image should be in the outermost layer of the cameras in order to avoid the deformation of the image.
Next, for the gamma-ray/hadron sepataion, we adopted Fisher Discriminant method [9] as described elsewhere [6]. Briefly stating, we made a linear combination of image parameres (hereafter we call it *FD*) as expressed by Eq. 1:

$$FD = \alpha_1 \cdot W_2 + \alpha_2 \cdot W_3 + \alpha_3 \cdot W_4 + \alpha_4 \cdot L_2 + \alpha_5 \cdot L_3 + \alpha_6 \cdot L_4 \quad (1)$$

where W_x and L_x are Width and Length observed by telescope x (Tx), and calculated the coefficients ($\alpha_1 \sim \alpha_6$) so that the difference of *FD* distributions between the gamma-ray events and hadron events was maximized. In this calculation, we used Monte Carlo simulation for gamma-ray events, and OFF-source run for hadron events. Since *FD* value has a small dependence on zenith angle due to the image size dependence on the same parameter, we corrected this effect by using OFF-source run distributions. We extracted gamma-ray events from fitting procedure of the ON-source *FD* distribution with background (OFF-source) distribution plus a scaled gamma-ray distribution [6]. In our Monte Carlo simulation, the overall light collecting efficiency (reflectivity of mirrors, quantum efficiencies of photomultiplier etc.) was estimated from a muon ring analysis [6], and we assumed the power-law index $\gamma = -2.1$ for the incident gamma-ray spectrum.

Finally, the incident direction of each Cherenkov image was calculated and the space angle, θ,

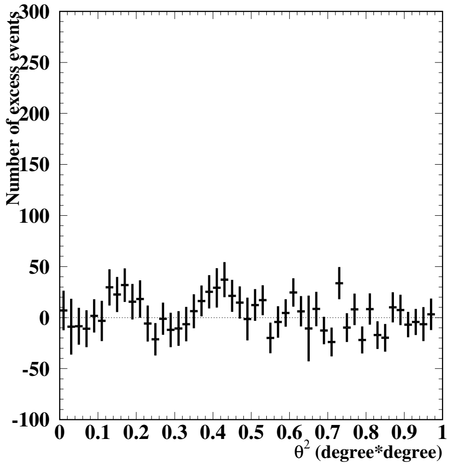

Figure 1: θ^2distribution of excess counts around the center of Abell 4038 (preliminary).

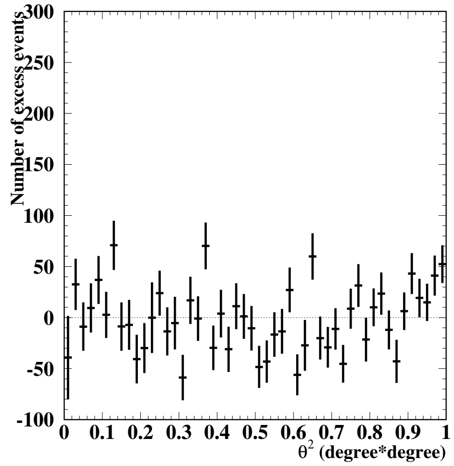

Figure 2: θ^2distribution of excess counts around the center of Abell 3667 (preliminary).

between the event and the assumed source position was assigned. Fig.1 and Fig.2 shows the θ^2 distribution for Abell 4038 and Abell 3667, respectively, after subtracting background distributions obtained from OFF-source runs. These preliminary plots show no hint of gamma-ray excess to appear toward $\theta^2 = 0$ if there is a point-like gamma-ray source in the cluster centers. We repeatedly plotted these distributions assuming grid points in the circle within 1° from the centers as possible point-like sources, but saw no hint of gamma-ray signal.

Thus we calculated 2σ upper limits from the cluster centers. In this calculation, we assumed the gamma-ray emission regions for two cases: point source emission region where we integrated inside $\theta^2 < 0^\circ.06$ by taking account of our angular resolution, and diffuse source emission region that is a circular region whose radius corresponds to a half of its Virial radius [10]. The results are shown in Fig.3 (Abell 4038) and Fig.4 (Abell 3667).

Discussion

The expected gamma-ray flux predicted by Inoue et al. [12] is proportional to the $M^{\frac{5}{3}}/D^2$ where M is the cluster mass and D is the distance to the cluster. So we scaled the predicted gamma-ray flux in their paper in which they assumed a Coma like cluster to the clusters in question (Abell 4038 & Abell 3667) and we overplotted them to the derived upper limits shown in Fig.3 and Fig.4. Comparison of the derived 2σ upper limits with the models, we can infer that the lower limits of the magnetic field in cluster's centers are $\sim 0.1\mu G$.

Summary

We observed clusters of galaxies Abell 4038 and Abell 3667 with the CANGAROO-III telescopes in 2006. From preliminary analysis, we could not find any gamma-ray excess within 1° circles from their centers. By comparing the upper limits with a theoritical model, we derived the lower limits of the magnetic filed around the cluster's centers as $\sim 0.1\mu G$.

Acknowledgements

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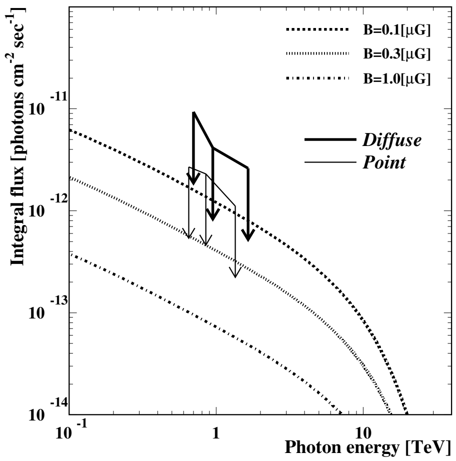

Figure 3: 2σ upper limits on gamma-ray emission around the center of Abell 4038 (preliminary). The thin arrows are upper limits assuming point source emission, and the thick arrows for diffuse source emission. The overplotted lines are the scaled theoritical models calculated in [12].

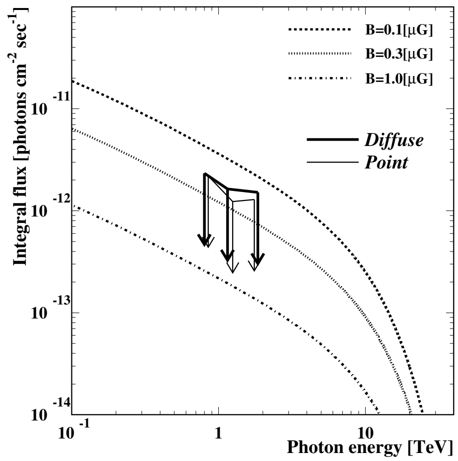

Figure 4: 2σ upper limits on gamma-ray emission around the center of Abell 3667 (preliminary). The thin arrows are upper limits assuming point source emission, and the thick arrows for diffuse source emission. The overplotted lines are the scaled theoritical models calculated in [12].

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