CANGAROO-III Search for TeV Gamma-rays from Two Clusters of Galaxies

R.Kiuchi[1], M.Mori[1], G.V.Bicknell[2], R.W.Clay[3], P.G.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[13], 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.L.Swaby[3], T.Tanimori[10], G.Thornton[3], F.Tokanai[5], K.Tsuchiya[16], S.Watanabe[10], 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, Chiba 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, Epping, NSW 2121, Australia
[5] Department of Physics, Yamagata University, Yamagata, Yamagata 990-8560, Japan
[6] Ibaraki Prefectural University of Health Sciences, Ami, Ibaraki, 300-0394, Japan
[7] Faculty of Management Information, Yamanashi Gakuin University, Kofu, Yamanashi 400-8575, Japan
[8] Department of Physics, Tokai University, Hiratsuka, Kanagawa 259-1292, Japan
[9] Department of Physics, Konan University, Kobe, Hyogo 658-8501, Japan
[10] Department of Physics, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan
[11] Faculty of Science, Ibaraki University, Mito, Ibaraki 310-8512, Japan
[12] Department of Physical Science, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan
[13] Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya, Aichi 464-8602, Japan
[14] National Astronomical Observatory of Japan, Mitaka, Tokyo181-8588, Japan
[15] School of Allied Health Sciences, Kitasato University, Sagamihara, Kanagawa 228-8555, Japan
[16] National Research Institute of Police Science, Kashiwa, Chiba 277-0882, Japan
E-mail (MM): morim@icrr.u-tokyo.ac.jp

Abstract

As accretion and merger shocks in clusters of galaxies may accelerate particles to high energies, clusters are candidate sites for the origin of ultra-high-energy (UHE) cosmic-rays. Recently, a prediction was presented for gamma-ray emission from a cluster of galaxies at a detectable level with modern imaging atmospheric Cherenkov telescopes. The gamma-ray emission was produced via inverse Compton upscattering of cosmic microwave background (CMB) photons by electron-positron pairs generated by collisions of UHE cosmic rays in the cluster. We have observed two clusters of galaxies, Abell 3667 and Abell 4038, searching for very-high-energy gamma-ray emission with the CANGAROO-III atmospheric Cherenkov telescope system in 2006. The analysis showed no significant excess around these clusters, yielding upper limits on the gamma-ray emission. By comparing the upper limit for the north-west radio relic region of Abell 3667 with the model prediction, we can derive a lower limit of the magnetic field of the region of $\sim 0.1\mu$G. This shows the potential of gamma-ray observations in studies of the cluster environment. We also discuss the upper limit from cluster center regions with a model of gamma-ray emission from neutral pion produced in hadronic collisions of cosmic-ray protons with the intra-cluster medium (ICM). The derived upper limit of the cosmic-ray energy density within this framework was one order higher than that of our Galaxy.

Key words: galaxies: clustrs – gamma-rays: observations

1. Introduction

Existence of non-thermal particles is suggested by observations of clusters of galaxies at various wavelengths (i.e. radio, optical, X-ray, and etc.) (e.g. Giovannini and Feretti 2004 and references therein). Cluster accretion and merger shocks could produce such high-energy particles, however accretion shocks may be more effective than merger shocks in particle acceleration due to their high Mach numbers (Miniati et al. 2000, Ryu et al. 2003). Cosmic ray electrons accelerated directly by these shocks may produce gamma-ray emission via inverse Compton (IC) scattering of the cosmic microwave background (CMB) (Totani and Kitayama 2000, Miniati 2003, Gabici and Blasi 2004). On the other hand, the accelerated cosmic ray protons can interact hadronically with the intra-cluster medium (ICM), and gamma-rays may be produced via π^0-decay (Völk et al 1996, Berezinsky et al. 2007, Pfrommer and Enßlin 2004) as well as IC emission by secondary electron/positron pairs from $\pi^{\pm}$-decay (Blasi and Colafrancesco 1999).

Observationally, no evidence of gamma-ray emission has been reported from clusters of galaxies (Reimer et al. 2003), though there is suggestive evidence (Totani and Kitayama 2000, Kawasaki and Totani 2002, Sharf and Mukherjee 2002). 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 TeV gamma-rays with atmospheric imaging telescopes yielded only upper limits (Hattori et al. 2003, Fegan et al. 2005, Perkins et al. 2006, Kiuchi et al. 2007, Domainko et al. 2007).

Recently, Inoue, Aharonian and Sugiyama (2005) 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 $p-\gamma$ 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 for the Coma cluster, for example, depending on mainly the strength of magnetic field in the cluster of galaxies.

Here we report preliminary results from our observations of two 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 those of the Coma cluster from the southern Abell catalog (Abell, Corwin Jr. and Olowin 1989): Abell 3667 is one of the brightest X-ray sources in the southern sky, and is also known to show huge diffuse radio emission around the cluster (Röttgering, Wieringa and Hunstead 1997). The location of its center is centered at $(\alpha, \delta) = (20^h 12^m 27.4^s, -56°49'36")$ (J2000), and its refshift is $z = 0.055$ (Sodré et al. 1992). Since the radio relics around Abell 3667 might be a site of particle acceralation (Knopp et al. 1996), it could be a good TeV gamma-ray candidate, however, the distance is a little farther than the Coma cluster ($z = 0.023$). Abell 4038, formerly known as Klemola 44, is an rich southern cluster with $z = 0.028$ with a cD galaxy at $(\alpha, \delta) = (23^h 47^m 45.1^s, -28°08'26")$ (J2000) (Slee et al. 2001).

2. Observation

We observed two clusters of galaxies, Abell 4038 and Abell 3667, with the CANGAROO-III telescopes (Mori et al. 2007) in 2006. Three telescopes (we call them as T2, T3 and T4) were used for these observations, and the data were recorded when any two telescopes were triggerd (Nishijima et al. 2005). 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 25 hours (ON) and 24 hours (OFF) for Abell 4038, and 32 hours (ON) and 29 hours (OFF) for Abell 3667.

3. Analysis

We basically followed analysis procedure explained in detail in Enomoto et al. (2006), 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* and *length* (Hillas 1985). The typical shower rate is $\sim$ 7 Hz, and we cut the data when the shower rate was lower than 5 Hz. The effective observation time for ON and OFF source after this selection is 18.7 hours and 17.7 hours for Abell 4038, and 28.7 hours and 23.7 hours for Abell 3667, respectively. After this shower image selection for each telescope, we selected only three-fold coincident events and also require that none of the shower images should be in the outermost layer of the cameras in order to avoid image truncation.

Next, for gamma-ray/hadron sepataion, we adopted the Fisher Discriminant method (Fisher 1936) as described elsewhere (Enomoto et al. 2006). Briefly stating, we made a linear combination of image parameres for each event (hereafter we call it FD) as expressed by:

$$FD = \alpha_1 W_1 + \alpha_2 W_3 + \alpha_3 W_4 + \alpha_4 L_2 + \alpha_5 L_3 + \alpha_6 L_4$$

where W_i and L_i are *width* and *length* observed by telescope i (Ti), and calculated the coefficients ($\alpha_1 \sim \alpha_6$) so that the difference of FD distributions between

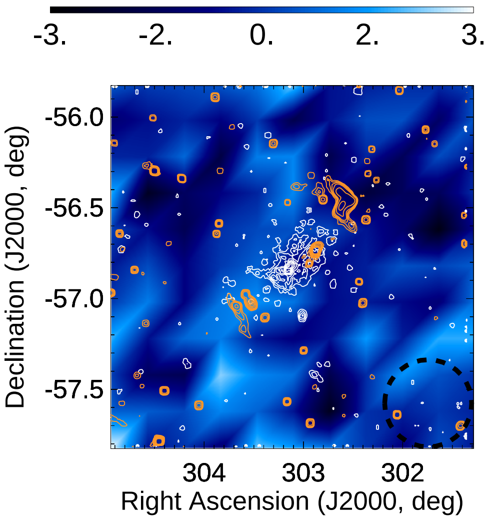

Fig. 1. Two-dimensional significance map of gamma-ray excess counts around Abell 3667. The map center is the cD galaxy, and contors of X-ray (ROSAT hard band: Voges et al. 1999) and radio (SUMSS 843 MHz: Mauch et al. 2003) intensities are overlaid.

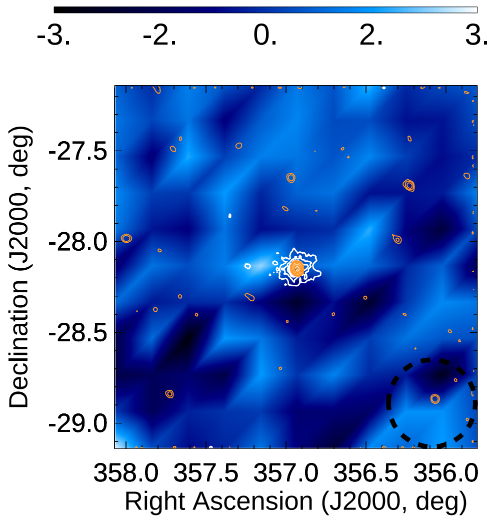

Fig. 2. Two-dimensional significance map of gamma-ray excess counts around Abell 4038. The map center is the cD galaxy, and contors of X-ray (ROSAT hard band: Voges et al. 1999) and radio (VLA 1.4 GHz: Condon et al. 1998) intensities are overlaid.

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 (Enomoto et al. 2006). 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 (Enomoto et al. 2006), and we assumed the power-law index of $\Gamma = -2.1$ for the incident gamma-ray spectrum.

4. Results

4.1. Two dimensional morphology and θ^2 distribution

With the procedures described in the previous section, we calculated two-dimensional (2D) significance maps around the cluster centers. We divided the regions (as the ON region) into $0.2^\circ \times 0.2^\circ$ square bins, and calculated the gamma-ray like excesses and their errors with the FD fitting method. Each background (OFF-source) bin was taken so that its position on the field-of-view would correspond to that of the bin of the ON region, but the areae was extended to 3×3 neighboring bins, to improve statistical accuracy. Fig. 1 and Fig. 2 show the resulting 2D significance maps of gamma-ray like excesses for Abell 3667 and Abell 4038, respectively. Since the gamma-ray acceptance falls off toward the outer part of the field-of-view, we limit the map to within 1 degree from the cluster centers. The significance distributions from all bins in 2D maps were well approximated by standard normal distributions for both regions, and we found no significant gamma-ray signals.

Next, the incident direction of each Cherenkov image was calculated and the space angle, θ, between the event and the assumed source position was assigned. Fig. 3 shows the θ^2 distributions for Abell 4038 (upper panel) and Abell 3667 (lower panel), after subtracting background distributions obtained from OFF-source runs. Also shown are the solid histograms of Monte Carlo simulation results for a Crab-like gamma-ray point source at each cluster center. These 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. Although there are some deviations in the θ^2 distributions, there are not statistically significant, considering our point spread function $\theta^2 < 0.06$ degree^2. In summary, there were no detectable point sources in the cluster fields.

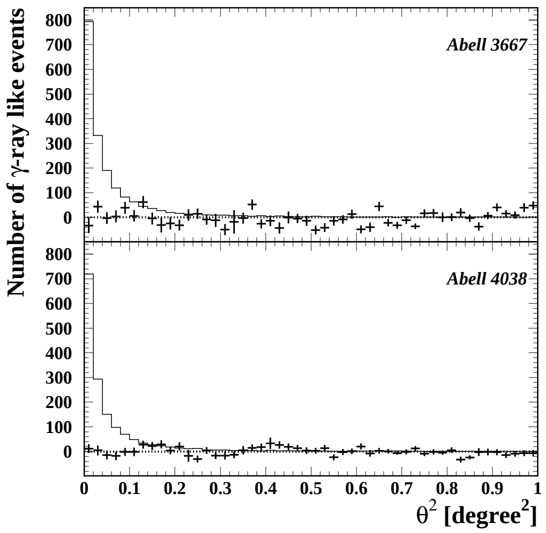

Fig. 3. θ^2 distribution of excess counts around the center of Abell 3667 (upper panel) and Abell 4038 (lower panel). The solid histograms show Monte Carlo simulation results for a Crab-like point source at each cluster center.

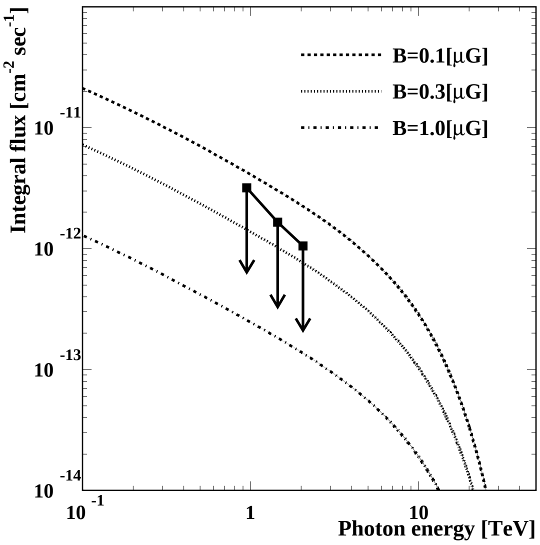

Fig. 4. Derived gamma-ray flux upper limits from NW Relic region of Abell 3667 (filled squares) with the prediction by Inoue, Aharonian and Sugiyama (2005). The model was scaled with the mass and the distance of Abell 3667.

4.2. Gamma-ray emission profiles and upper limits

We also adopted several gamma-ray emission profiles in the cluster fields, and searched the diffuse gamma-ray signals. First, we defined two circular regions (hereafter *NW/SE Relic* region) which cover the prominent radio relics around Abell 3667, since they may represent a shock morphology. The center coordinates (R.A. & Dec. in J2000) and their radii were defined as follows: $(20^h10^m24^s, -56°27'00'')$ and 0.30° for *NW Relic* region, $(20^h14^m36^s, -57°03'00'')$ and 0.24° for *SE Relic* region.

We may expect that gamma-ray emission via π^0-decay might be concentrated toward the cluster center regions. It is well known that many clusters have a diffuse X-ray morphology at their centers which may trace thermal components bounded by the gravitational potential of clusters. We thus assume that the gamma-ray emission profile would trace the X-ray morphology of clusters. We looked at the *ROSAT* PSPC data for the X-ray morphology. The peak positions of the X-ray brightness are almost coincident with the cD galaxies of the clusters, which were the tracking points of our observations. We then defined two regions (hereafter *Cluster Core* regions) such that their centers were at the position of the cD galaxies and the radii were equal to the point where the S/N of the *ROSAT* data fell below ~ 3, which was 0.40° for Abell 3667 and 0.26° for Abell 4038, as described in Table 2 of Mohr et al. (1999). In our Monte Carlo simulation, gamma-rays were generated uniformly within the defined area with a power-law spectrum of index $\Gamma = -2.1$.

The gamma-ray excess count for each region was calculated by the *FD* fitting method as before. The *FD* distribution of each region fitted with that of OFF-source region and that of gamma-ray events from Monte Carlo simulation are compared, but, there are no significant excesses which exceed 3σ. Therefore, we calculated the 2σ upper limits on the gamma-ray integral fluxes from these regions. The obtained flux upper limits are shown in Fig. 4 for *NW Relic* region of Abell 3667 and Fig. 5 for *Cluster Core* region of Abell 4038.

5. Discussion

The theory by Inoue, Aharonian and Sugiyama (2005) predicts gamma-ray emission at accretion shocks around a massive cluster. We searched for gamma-ray emission from the radio relics of Abell 3667, assuming that they might trace the accretion shock (Enßlin et al. 1998), although it has also been suggested that the relics are the results of a major merger (Röttigering et al. 1997) in which case the particle acceleration would not be as strong as assumed in the accretion model. However, we found no evidence of gamma-ray emission from either region. Since the magnetic field of Abell 3667 was estimated for the area of the cluster center and the northwest relic so far (Johnston-Hollitt, 2003), we compared the derived upper limits from *NW Relic* region with the

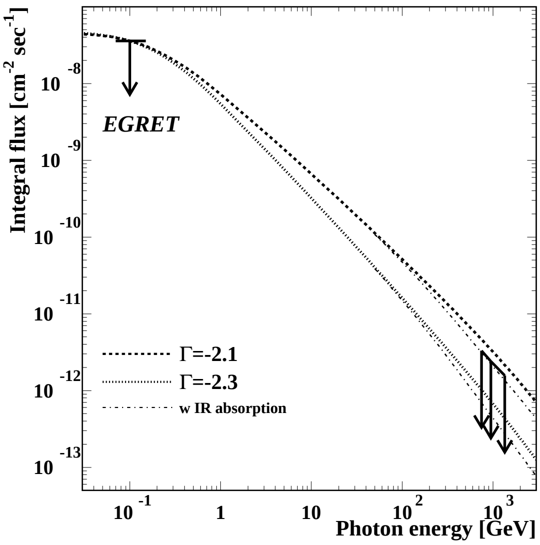

Fig. 5. Derived gamma-ray flux upper limits from the *Cluster Core* region of Abell 4038 with the gamma-ray emission spectrum via π^0-decay process, normalized to the EGRET upper limits (Reimer et al. 2003). The gamma-ray absorption effect by extragalactic infrared photons are shown by dot-dashed lines, where the P0.4 model given in Aharonian et al. (2006) is adopted.

model prediction in Fig. 4. The model assumes a proton luminosity of one tenth of the kinetic energy flux through strong accretion shocks, which depends on the cluster mass in the form of $\propto M^{5/3}$ (see Eq.(2) in Inoue, Aharonian and Sugiyama (2005)), and we scaled the predicted gamma-ray flux according to the mass (M) and distance (d) of Abell 3667 from the parameters (Coma-like cluster) used in their model ($M = 2\times10^{15} M_\odot$, $d = 100\,\mathrm{Mpc}$). The mass of Abell 3667 has been estimated using the Virial relation (Sodré et al. 1992, Girardi et al. 1998), and here we adopt $M = 2\times10^{15}h^{-1}M_\odot$. The scaled fluxes are shown in Fig. 4 with lines assuming magnetic fields of 0.1μG, 0.3μG, and 1.0μG.

Fig. 4 indicates that we can set a lower limit for the magnetic field in these clusters to be $\sim 0.1\mu$G, within the framework of the model by Inoue, Aharonian and Sugiyama (1995). This value is not a strong constraint on the magnetic field when it is compared with the other estimation, e.g., a few μG from Faraday rotation measurements (see Johnston-Hollitt (2003) for other results), however, this is the first example to show the potential of TeV gamma-ray observations to study physical parameters of the cluster environment. Note that the above flux upper limits also provide a constraint on the gamma-ray emission via primary electron IC which is assumed to appear at the cluster shocks (Miniati 2003).

We also searched for gamma-ray emission from the *Cluster Core* regions, deriving flux upper limits. The gamma-ray flux via π^0-decay, produced in the hadronic collisions of the high-energy protons with the ICM, is thought to be the brightest at the cluster centers, and its flux level is usually discussed from the aspect of the effective confinement of cosmic-rays inside the cluster during a Hubble time. Here we consider the total cosmic-ray energy stored inside the cluster centers. We plotted the flux upper limits from the Abell 4038 *Cluster Core* region together with the EGRET upper limit (Reimer et al. 2003) in Fig. 5. Völk and Atoyan (2005) assumed that the high-energy protons were accumulated in a cluster through supernova explosions and predicted a proton spectrum in the power-law forn of an index $\Gamma = -2.1$ with an energy cutoff of $E_{\max} = 200\,\mathrm{TeV}$. We adopted their parameters, and the gamma-ray absorption effect by the extragalactic background infrared radiation (P0.4 model in Aharonian et al. (2006)) was also incorporated. The gamma-ray spectra were represented by lines in Fig. 5, which were scaled to be consistent with the EGRET upper limits.

As shown in Fig. 5, the EGRET and CANGAROO-III results for Abell 4038 gave almost the same constraint on the gamma-ray emission for the case of $\Gamma = -2.1$, and the total cosmic-ray energy to explain our flux upper limits is 1.2×10^{63} erg, using an ICM density of 10^{-3} cm^{-3}, which is a typical value for cluster centers (Blasi et al. 2007). We then derived the upper limit of the cosmic-ray energy density within the *Cluster Core* region of Abell 4038, as $\sim$40 eV cm^{-3}, assuming a spherical symmetry with the radius we defined for this region. This value is one order of magnitude higher than that of our Galaxy, $\sim$1 eV cm^{-3}, however, it opens the door to discussions of the non-thermal component in the clusters. The same estimation was made for the *Cluster Core* region of Abell 3667 as well, though we obtain a higher upper limit than that for Abell 4038.

6. Summary

We observed two clusters of galaxies, Abell 3667 and Abell 4038, searching for very-high-energy gamma-ray emission with the CANGAROO-III atmospheric Cherenkov telescope system in 2006. No significant excess was detected from both clusters, and flux upper limits on the gamma-ray emission were obtained. By comparing the upper limit for the north-west radio relic region of Abell 3667 with a model prediction, we can derive a lower limit for the magnetic field of the region of $\sim 0.1\mu$G. We also discussed the flux upper limit from cluster center regions with a gamma-ray emission model via the decay of π^0 produced in hadronic collisions of cosmic-ray protons with the ICM. The upper limit of the cosmic-ray energy density stored within the Abell 4038 cluster center was estimated to be $\sim$40 eV cm^{-3} by imposing some assumptions, such as the ICM density, and this value is one order higher than that of our Galaxy. These estimations show the potential of gamma-ray observations in studies of the cluster environment.

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