CANGAROO-III SEARCH FOR TeV GAMMA RAYS FROM TWO CLUSTERS OF GALAXIES

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ABSTRACT

Because 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. A prediction was presented for gamma-ray emission from a cluster of galaxies at a detectable level with the current generation of imaging atmospheric Cherenkov telescopes. The gamma-ray emission was produced via inverse Compton upscattering of cosmic microwave background photons by electron–positron pairs generated by collisions of UHE cosmic rays in the cluster. 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. The analysis showed no significant excess around these clusters, yielding upper limits on the gamma-ray emission. From a comparison of the upper limit for the northwest radio relic region of Abell 3667 with a model prediction, we derive a lower limit for the gamma-ray emission from a cluster of galaxies at a detectable level with the current generation of imaging atmospheric Cherenkov telescopes. This shows the potential of gamma-ray observations in studies of the origin of UHE cosmic rays.

Key words: gamma rays: observations – galaxies: clusters: individual (Abell 3667, Abell 4038) – galaxies: magnetic fields

1. INTRODUCTION

Clusters of galaxies are the largest systems in the universe that are gravitationally bound, and they are potential sources of ultra-high-energy (UHE) cosmic rays, since their sizes and moderate magnetic fields allow a high maximum energy (∼10^{19} eV) in acceleration (Ostrowski 2002). Although cluster accretion and merger shocks could produce such high-energy particles, 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 & Kitayama 2000; Miniati 2003; Gabici & Blasi 2004). On the other hand, accelerated cosmic-ray protons can interact hadronically with the intracluster medium (ICM), and gamma rays may be produced via π^{0}-decay (Völk et al. 1996; Berezhnsky et al. 1997; Pfrommer & Enßlin 2004) as well as IC emission by secondary electron–positron pairs from π^{0}-decay (Blasi & Colafrancesco 1999).

Observations of clusters of galaxies at various wavelengths (e.g., radio, EUV, X-ray) suggest the existence of non-thermal particles in these gigantic objects (Fusco-Femiano et al. 2001; Nevalainen et al. 2004; Bowyer et al. 2004; Giovannini & Feretti 2004). However, at gamma-ray energies, no observational evidence has been reported from clusters of galaxies (Reimer et al. 2003), though there is suggestive evidence (Kawasaki & Totani 2002; Scharf & Mukherjee 2002). Observations in the TeV energy band with imaging atmospheric Cherenkov telescope (hereafter IACT) experiments have yielded the only upper limits to date (Hattori et al. 2003; Fegan et al. 2005; Perkins et al. 2006; Domainko et al. 2007).

Recently, Inoue et al. (2005) considered protons, accelerated up to 10^{18–19} eV by accretion shocks around a massive...
cluster, interacting with the CMB photons, with secondary electron–positron pairs produced in the $p\gamma$ process, boosting those photons into the TeV energy range by IC scattering. Although their prediction depends on many physical parameters, the predicted gamma-ray flux could be at a detectable level for current IACT experiments for massive, nearby clusters. Thus, observations of clusters of galaxies with IACTs probe high-energy processes and the environment in these large-scale systems, and if gamma-ray signals are detected, they may also provide clues to help solve the mystery of UHE cosmic-ray production. If there is no detected signal, we can place limits on the physical parameters of clusters, such as the strength of the magnetic field.

In this paper, we report on a search for TeV gamma-ray emission from two clusters of galaxies, Abell 3667 and Abell 4038, with CANGAROO-III, an array of IACTs. We selected these targets according to their high masses and relative closeness from the southern Abell catalog (Abell et al. 1989).

Abell 3667, also known as SC 2009-57, is classified as type L in the Rood–Sastry system (Rood & Sastry 1971) due to the linear arrangement of the galaxies, including two of the brightest D galaxies. The cluster has a redshift of $z = 0.055$ (Sodré et al. 1992), and is centered at $\alpha(2000) = 20^h12^m27.4^s$, $\delta(2000) = -56\degree49'36''$, which is the location of the brightest D galaxy (Knopp et al. 1996). The cluster is one of the brightest X-ray sources in the southern sky (Edge et al. 1992), and is also known to show significant diffuse radio emission around its center (Röttgering et al. 1997).

Abell 4038, also known as Klemola 44, is a rich southern cluster with $z = 0.028$, and is classified as type cD in the Rood–Sastry system, where the cD galaxy is centered at $\alpha(2000) = 23^h47^m45.1^s$, $\delta(2000) = -28\degree08'26''$ (Slee et al. 2001). An X-ray image shows an extended morphology, and there is a radio relic near the cD galaxy (Slee and Roy 1998), though it is smaller than the point-spread function (PSF) of typical IACTs ($\sim0\degree1$).

The search described in the following sections focused on the detection of point sources within the cluster fields as well as looking for gamma-ray signals from several regions by assuming gamma-ray emission models: The giant radio relics around Abell 3667 may indicate the sites of shocks, where particle acceleration occurs effectively, and thus gamma-ray emission could be expected from the relics by the scenario of the UHE proton origin (Inoue et al. 2005). Apart from the shock regions, the density of the ICM is highest at the cluster centers, so the gamma-ray flux via $\pi^0$-decay would be strongest there.

In Section 2, we introduce the CANGAROO-III telescope systems and observations of the clusters. The data-analysis procedures are explained in Section 3, and the main results together with a definition of the gamma-ray search regions are described in Section 4. Finally, a discussion of the gamma-ray emission from clusters of galaxies based on the CANGAROO-III results is presented. Throughout this paper, we assume a Hubble constant of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

### 2. INSTRUMENT AND OBSERVATIONS

Two clusters of galaxies, Abell 3667 and Abell 4038, were observed in the TeV energy band using the imaging atmospheric Cherenkov technique with the CANGAROO-III telescope system (Enomoto et al. 2006a), located near Woomer, South Australia (136°786E, 31°099S, 160 m a.s.l.). The system consists of four telescopes, which are located at the corners of a diamond with 100 m sides (Enomoto et al. 2002). The first telescope, which we call T1, was not used in these observations, since its current performance is inferior to that of the other telescopes. The specifications of the second, third, and fourth telescopes, hereafter called T2, T3, and T4, are almost the same: they have segmented paraboloid reflector 10 m in diameter and 8 m in focal length. Each reflector is composed of 114 spherical mirror facets, and the total mirror area is 54 m$^2$ (Kawachi et al. 2001). At each focus there is an imaging camera, which is an array of 427 photomultipliers (PMTs). Each PMT covers a sky field of $0\degree17$ in diameter, and the total field of view (FOV) is about $4\degree$, suitable for applying analysis using an imaging technique (Kabuki et al. 2003). The data acquisition system is triggered when at least two telescopes have signals coinciding for more than 10 ns within a 650 ns time window, thus eliminating muon events that mostly trigger a single telescope (Nishijima et al. 2005). Then, the amplitude and the arrival times of signals from PMTs are digitized by ADC/TDC modules, and recorded for offline analysis (Kubo et al. 2001).

The observations were carried out for ON-source and OFF-source tracking runs. For OFF-source runs, the target position was shifted in right ascension so that the telescopes tracked the same trajectory across the sky as ON-source runs. Also, we adopted wobble mode observations for both ON-source and OFF-source runs, in which the pointing direction was shifted in declination by $\pm0\degree5$ from the target direction every 20 minutes. One of the advantages of the wobble mode is to average the response of PMTs, since the target position rotates on the FOV. All observations were made on moonless nights from 2006 July to September. Details of the data sets are summarized in Table 1.

In addition to the observations, we also observed dark regions (with no bright stars or gamma-ray sources in the FOV) without imposing the telescope coincidence described above, and we extracted local muon-ring events from these data to monitor the total performance of the telescopes (Enomoto et al. 2006a). This calibration (denoted muon run) was done every month, and their statistics are also shown in Table 1.

### 3. DATA ANALYSIS

We followed the analysis procedure explained in detail in Enomoto et al. (2006a), which we briefly describe here.

First, raw data were calibrated, using daily calibration runs using LEDs (Kabuki et al. 2003). We then selected the shower events from the calibrated data sets. For each triggered event, camera pixels that recorded less than 5 p.e. were discarded so as to remove any night-sky-background photons, and shower events were extracted from the remaining pixels, imposing the conditions that there were at least five adjacent hit pixels, and that the pixels were triggered within $\pm30$ ns from the mean arrival time of all hit pixels. This procedure cleaned the shower images and separated random noise, such as multiple
night-sky-background photons. The typical shower event rate was $\sim 7$ Hz (average over 5 minutes), and we excluded the data from the analysis when the shower event rate was below 5 Hz so as to remove any data affected by clouds etc. The effective total observation times for the selected data sets, taking account of the dead time in data acquisition, are summarized in Table 1. After this image-cleaning procedure, we discarded events with any hits in the outermost layer of the imaging cameras since such shower images may be distorted (Enomoto et al. 2006b).

Next, image moments (width and length) of showers were calculated as defined by Hillas (1985), and the arrival direction of the shower was reconstructed event by event, by minimizing the sum of the squared widths of the images weighted by their total photoelectron numbers seen from the assumed direction, as described in Kabuki et al. (2007).

Finally, gamma-ray/hadron separation was carried out by applying the Fisher discriminant method (Fisher 1936; Enomoto et al. 2006a). In this method, the Fisher discriminant (hereafter FD) is defined as a linear combination of the image moments

$$FD = \sum_{i=1}^{6} \alpha_i \cdot P_i,$$

where $P = (W_2, W_3, W_4, L_2, L_3, L_4)$ is a set of energy-corrected width and length of shower images of three telescopes. The coefficients, $\alpha_i$ ($i = 1-6$), were determined so that the difference of the FD distribution of gamma-ray events and that of hadron events would be maximized. We used Monte Carlo simulation data as gamma-ray events, and OFF-source run data as background hadron events for deriving the coefficients. We then extracted gamma-ray events from ON-source run data by fitting the ON-source FD distribution with that of the background (OFF-source) distribution plus the gamma-ray distribution. Our Monte Carlo simulation code is based on GEANT3, the details are described in Enomoto et al. (2002), where some parameters such as the geometry of the telescopes are replaced with those of the current CANGAROO-III system. The degradation of the overall light collection efficiency (including reflectivities of the reflectors, quantum efficiencies of PMTs, etc.) and the spot size of each telescope were estimated from a muon-ring analysis (Enomoto et al. 2006a) using muon run data, and they were included in our simulation. In the gamma-ray simulation, we assumed a power-law spectrum index of $\gamma = -2.1$, which is often assumed for clusters of galaxies (e.g., Völk & Atayan 2000).

4. RESULTS

4.1. Two Dimensional Morphology and $\theta^2$ Distribution

First, we calculated the two-dimensional (2D) significance map around the cluster centers. We divided these (ON source) regions into $0.2 \times 0.2$ square bins, and calculated the gamma-ray-like excesses and their errors with the FD fitting method, described in the previous section. Each background (OFF-source run) bin was taken so that its position on the FOV would correspond to that of the ON region's bin, but the area was extended to $3 \times 3$ neighboring bins, to improve the statistical accuracy. Figure 1 shows the resulting 2D significance maps of gamma-ray-like excesses. Since the gamma-ray acceptance falls off toward the outer part of the FOV, we limit the map to within $1^\circ$ from the cluster centers. The significance distributions from all bins in 2D maps were well approximated by standard normal distributions for both regions. The best-fit Gaussians have mean values of $0.02 \pm 0.10$ (Abell 3667) and $0.17 \pm 0.11$ (Abell 4038), with standard deviations of $1.08 \pm 0.08$ (Abell 3667) and $1.02 \pm 0.08$ (Abell 4038), and there are no significant gamma-ray signals.

Next, we show the $\theta^2$ distribution, where $\theta$ is the space angle between the target position and the reconstructed arrival direction, from the cluster centers in Figure 2. The background bin for calculating each $\theta^2$ bin was taken from the OFF-source region to correspond to the position in the FOV. Although there were deviations in the $\theta^2$ distributions, they were not significant ($<3\sigma$), considering our PSF ($\theta^2 < 0.06$ deg$^2$).

In summary, there were no detectable point sources in the cluster fields.

4.2. Gamma-ray Emission Profiles and Upper Limits

We also adopted several gamma-ray emission profiles in the cluster fields, and searched for diffuse gamma-ray emission. First, we defined two circular regions (hereafter NW/SE Relic regions) that cover the prominent radio relics around Abell 3667, since they may represent a shock morphology. The center coordinates (R.A. and decl. in J2000) and their radii were defined
as follows: (20h10m24s, −56°27′00″) and 0′′30 for the NW Relic region, (20h14m36s, −57°03′00″) and 0′′24 for the SE Relic region.

We expect that gamma-ray emission via π^0-decay is concentrated at 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 traces the X-ray morphology of clusters. We adopted 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 signal-to-noise ratio (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). For Abell 3667, more recent observations with higher resolution have been reported (e.g., XMM-Newton (Briel et al. 2004); Chandra (Vikhlinin et al. 2001)). Chandra has a limited FOV for our purpose, however, XMM showed that the signal region above the background noise level was in the central 11′ which can be regarded as being a point source, considering the positional resolution of CANGAROO-III. So we first searched for gamma-ray signals from the Abell 3667 center region based on ROSAT data, and we later discuss the case of a point source, especially concerning the cosmic-ray energy density. With the π^0-decay model, Völk & Atoyan (2000) assumed that the high-energy protons were accumulated in a cluster through supernova explosions, and that the predicted proton spectrum forms the power-law index Γ = −2.1 with an energy cutoff of E_{\text{max}} = 200 TeV. So in our Monte Carlo simulation, gamma rays were generated uniformly within the defined area with a power-law spectrum having an index of γ = −2.1.

The gamma-ray events from each region were 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 a Monte Carlo simulation is shown in Figure 3. A gamma-ray signal would appear around FD = 0 (see, e.g., Figure 1 in Enomoto et al. 2006b); however, the calculated significances from the four regions did not exceed 3σ, and so there is no evidence of extended emission.

Therefore, we calculated the 2σ upper limits on the integral gamma-ray fluxes from these regions. The obtained flux upper limits, their threshold energy, and the definition of each region are summarized in Table 2.

5. DISCUSSION

Inoue et al. (2005) predicted gamma-ray emission at accretion shocks around a massive cluster. We searched for gamma-ray emission from 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 (Roettiger et al. 1999) in which case the particle acceleration would not be as strong as assumed in the accretion model. We found no evidence of gamma-ray emission from either region. Since estimations of the magnetic field of Abell 3667 have been made for the area of the cluster center and the northwest relic so far (Johnston-Hollitt 2004), we compared the derived upper limits from NW Relic region with the model prediction, as shown in Figure 4. The model assumes a proton luminosity of one-tenth of the kinetic energy flux through strong

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**Table 2**

| Cluster   | Region    | R.A. (J2000) | Decl. (J2000) | Radius (deg) | Threshold (TeV) | 2σ Upper Limit (cm^{-2} s^{-1}) |
|-----------|-----------|--------------|--------------|--------------|----------------|----------------------------------|
| Abell 3667 | NW Relic  | 20h10m24s    | −56°27′00″   | 0.30         | 0.95           | 3.19 × 10^{-12}                 |
|           |           |              |              |              | 1.45           | 1.64 × 10^{-12}                 |
|           |           |              |              |              | 2.05           | 1.05 × 10^{-12}                 |
|           | SE Relic  | 20h14m36s    | −57°03′00″   | 0.24         | 0.85           | 5.69 × 10^{-12}                 |
|           |           |              |              |              | 1.35           | 1.86 × 10^{-12}                 |
|           |           |              |              |              | 2.05           | 1.55 × 10^{-12}                 |
|           | Cluster Core | 20h12m27′4  | −56°49′36″   | 0.40         | 0.95           | 5.52 × 10^{-12}                 |
|           |           |              |              |              | 1.35           | 2.91 × 10^{-12}                 |
|           |           |              |              |              | 1.95           | 2.12 × 10^{-12}                 |
| Abell 4038 | Cluster Core | 23h47m45′1  | −28°08′26″   | 0.26         | 0.75           | 3.30 × 10^{-12}                 |
|           |           |              |              |              | 0.95           | 2.41 × 10^{-12}                 |
|           |           |              |              |              | 1.35           | 1.57 × 10^{-12}                 |
accretion shocks, which depends on the cluster mass in the form of $\propto M^{5/3}$ (see Equation (2) in Inoue et al. 2005), and we scaled the predicted gamma-ray flux according to the mass ($M$) and distance ($d$) of Abell 3667 from the (Coma-like cluster) parameters used in their model ($M = 2 \times 10^{15} M_{\odot}$, $d = 100$ Mpc). The mass of Abell 3667 has been estimated using the Virial relation to be $3.7 \times 10^{15} M_{\odot}$ (Sodr´ee et al. 1992) or $1.7 \times 10^{15} M_{\odot}$ (Girardi et al. 1998), so here we adopt a cluster mass of their mean value, $(2.1 \times 10^{15} M_{\odot})$. The scaled fluxes are shown in Figure 4 with lines for magnetic fields of 0.1 $\mu$G, 0.3 $\mu$G, and 1.0 $\mu$G.

Figure 4 indicates that we can set a lower limit for the magnetic field in the cluster to be $\sim 0.1 \mu$G, within the framework of the model by Inoue et al. (2005). This value is not a strong constraint on the magnetic field when it is compared with other estimates, e.g., a few $\mu$G from Faraday rotation measurements (see Johnston-Hollitt 2004 for other results); however, the result provides an independent method of a magnetic field estimation, using TeV gamma-ray observations. The flux upper limits from the $SE$ Relic region were higher than that of the $NW$ Relic, and the lower limit of the magnetic field strength was estimated to be $\sim 0.1 \mu$G, depending on the assumed cluster mass. Note that the above flux upper limits also provide a constraint on the gamma-ray emission via primary electron IC emission, which is believed to appear at the shocks (Miniati 2003).

We also searched for gamma-ray emission from the Cluster Core regions, deriving flux upper limits. The gamma-ray flux via $\pi^0$-decay, produced in hadronic collisions of high-energy protons with the ICM, is thought to be brightest at the cluster centers, and its flux level is usually discussed from the perspective of an effective confinement of cosmic rays inside a cluster during the Hubble time. Here, we discuss the total cosmic-ray energy stored inside the cluster centers, using the CANGAROO-III result. We plotted the flux upper limits from the Abell 4038 Cluster Core region together with the EGRET upper limit (Reimer et al. 2003) in Figure 5. We adopted the assumptions of Völk & Atoyan (2000), as introduced in a previous section, and the gamma-ray absorption effect by IR photons (P0.4 model in Aharonian et al. 2006) was also incorporated. The gamma-ray spectra were represented by lines in Figure 5, which were scaled to be consistent with the EGRET upper limits.

As shown in Figure 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 $1.2 \times 10^{63}$ 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 that we defined for this region. The same estimation was applied for the Cluster Core region of Abell 3667 as well, and the upper limit was calculated to be $\sim 20$ eV cm$^{-3}$. Two factors should be considered for this value: as described in Section 1, the morphology of Abell 3667 is elongated toward two radio relics, rather than a simple sphere, so the assumption of a spherical symmetry might need to be reexamined where the cluster type of Abell 4038 is cD. Also, if we adopt the $XMM$ results, the search region is effectively a point source, as described beforehand. In this case, a lower flux upper limit is obtained, and the total volume of the search region also decreased, with the cosmic-ray energy density increasing to $\sim 40$ eV cm$^{-3}$, which was the same level for Abell 4038. In any case, the derived values are 1 order of magnitude higher than
is adopted. The gamma-ray absorption effect by IR photons are represented by dot-dashed lines, where the P0.4 model in Aharonian et al. (2006) is adopted.

![Figure 5](http://glast.gsfc.nasa.gov/) Derived gamma-ray flux upper limits from the Cluster Core region of Abell 4038 with the gamma-ray emission spectrum via $\pi^0$-decay process, normalized to the EGRET upper limits (Reimer et al. 2003). The EGRET upper limits are indicated by arrows at 100 MeV, and the lines are the gamma-ray spectrum from the proton power-law indices of $\Gamma = -2.1$ and $-2.3$ with an energy cutoff of 200 TeV. The gamma-ray absorption effect by IR photons are represented by dot-dashed lines, where the P0.4 model in Aharonian et al. (2006) is adopted.

**Table 3** Summary of Various Limits on the Clusters

| Region          | 2$\sigma$ Upper Limit $^a$ (cm$^{-2}$ s$^{-1}$) | Magnetic Field (µG) | Energy Density (eV cm$^{-3}$) |
|-----------------|---------------------------------|--------------------|-------------------------------|
| A3667 NW Relic  | 3.19 x 10^{-12}                 | >0.1               | ...                           |
| A3667 SE Relic  | 5.69 x 10^{-12}                 | >0.1               | ...                           |
| A3667 Cluster Core $^b$ | 5.52 x 10^{-12}  | ...               | <20                           |
| II. $^c$        | 2.03 x 10^{-12}                 | ...               | <40                           |
| A4038 Cluster Core | 3.30 x 10^{-12}  | ...               | <40                           |

Notes. The defined regions, gamma-ray flux upper limits, lower limit of magnetic field, and cosmic-ray energy density.

$^a$ The threshold energy was listed in Table 2.

$^b$ Based on ROSAT data.

$^c$ Based on XMM-Newton data (point-source analysis).

that of our Galaxy, ~1 eV cm$^{-3}$, opening the door to discussions of the non-thermal component in the clusters. All the calculated upper limits are summarized in Table 3.

Further observations of clusters of galaxies in the TeV band by next-generation IACTs currently in the planning stage, such as CTA$^{18}$ or AGIS, and in the GeV band by GLAST$^{20}$ will open a new window in the research of high-energy phenomena of clusters of galaxies with their improved sensitivities.

6. CONCLUSION

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 the clusters, and flux upper limits on the gamma-ray emission were obtained. By comparing the upper limit for the northwest radio relic region of Abell 3667 with a model prediction, we can derive a lower limit for the magnetic field of the region of ~0.1 µG. We also discussed the flux upper limit from the cluster center regions using a gamma-ray emission model via the decay of $\pi^0$ produced in hadronic collisions of cosmic-ray protons with the ICM. The upper limit of the cosmic-ray energy density stored within cluster centers was estimated to be ~40 eV cm$^{-3}$ by imposing some assumptions, such as the ICM density, and the values are 1 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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