Status of an Atmospheric Cherenkov Imaging Camera for the CANGAROO–III Experiment and Perspective of the Field

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Summary. CANGAROO–III is an experiment aiming at studying the properties of very high energy gamma rays from celestial objects in the southern sky. We use an array of 4 imaging atmospheric Cherenkov telescopes in Australia. The observation with the first telescope (CANGAROO–II) started in 1999 and the data have been analyzed. The second telescope was constructed in 2002 and stereoscopic observations started. This contribution summarizes the status of the CANGAROO–III experiment and physics results with the first telescope.

1 Introduction

CANGAROO is an acronym for Collaboration of Australia and Nippon(Japan) for a Gamma-Ray Observatory in the Outback. This project is set up with the aim of observing Very High Energy(VHE) gamma rays (100GeV–100TeV) from celestial objects. The VHE gamma-ray astronomy is a rapidly developing field. Reviews on this field can be found in [1] [2] [3] [4] and also in Professor Lorenz's talk [5]. We started this international project in 1992 with the CANGAROO–I telescope whose diameter was 3.8m [6]. Now this project has evolved to the CANGAROO–III which is an array of four 10m telescopes.

A gamma-ray energy of 1 GeV corresponds to a temperature of 10^{13} K if the gamma ray is produced as thermal radiation. It is difficult to find such high temperature state in the present universe. Thus these gamma rays are produced by the high energy cosmic rays (protons and electrons) which have been accelerated in the celestial objects, that is, non-thermal radiation.

There are two approaches to observe cosmic gamma-rays – from space satellites and ground-based telescopes. The Compton Gamma Ray Observatory (CGRO) was launched in 1991. The EGRET detector [7] on board CGRO detected gamma rays in the energy region from 30 MeV to 20GeV. A total of 271 point sources were detected [8] including 5 pulsars and 66 active galactic nuclei, but 170 sources were left as unidentified sources. They were astonishing discoveries of high energy phenomena in the universe. The CANGAROO–III experiment is based on the other approach - the ground-based Cherenkov telescopes.

2 The techniques of VHE gamma-ray astronomy

2.1 Cherenkov Telescope

The search for Very High Energy(VHE) gamma rays (>1TeV) was attempted in the early 1960s. Primary gamma rays inject into the upper atmosphere and generate the cascade of electrons and positrons. The charged particles emit Cherenkov light and we can detect the feeble light with ground based optical telescope. Similarly, cosmic rays generate cascades with hadronic interaction and emit Cherenkov light, which is the background. Distinguishing gamma rays from background cosmic rays, however, was difficult.

The Whipple telescope (Arizona, USA) was equipped with the first imaging Cherenkov system consisting of 37 photo-multiplier tubes(PMTs). In 1989, the Whipple group detected a strong signal (9.0 σ significance level) from the Crab using the imaging method [9]. The detection of gamma rays from an Active Galactic Nuclei(AGN), Markarian 421 [10], established the imaging method with Cherenkov telescope (large reflector with small pixeled PMT camera). Later, many groups detected Crab nebula and new objects such as AGN, pulsars and supernova remnants in 1990s [4].

The CANGAROO group started observations in the southern hemisphere (Woomera, Australia)(Fig. 1). The observation site is located in the desert to avoid artificial light. The 3.8m telescope (CANGAROO–I) was operated between 1992 and 1998 [11] and investigated the gamma rays from pulsars (PSR 1706-44 [12], Vela [13], PSR B1509-58 [14]) and SNRs (SN1006 [15], RXJ1713.7-3946 [16]). Successful operation of the 3.8m telescope led the CANGAROO group to make the larger telescope with fine resolution camera. In 1999, CANGAROO–II 7m telescope was constructed and was upgraded to 10m in 2000 [17]. The large mirror reduced the energy threshold of gamma ray into 400GeV at zenith. The CANGAROO–II 10m telescope has observed a lot of objects in the southern sky. The result of CANGAROO–II is mentioned in the later section.

2.2 Imaging analysis

Monte Carlo simulation indicates that the typical Cherenkov image expected from gamma-rays has a compact and elliptical shape with its major axis presumably oriented towards the center of field of view. In contrast, Cherenkov images from hadron cosmic-ray showers are much more irregular and randomly oriented in the focal plane. The difference between images produced in gamma-ray and cosmic-ray showers can be quantified by Monte Carlo simulations (for gamma rays) and OFF-source data (for cosmic rays). The parameter "Alpha", the image orientation angle, is the final signpost to judge the gamma-ray signals from the objects.

2.3 Stereoscopic observation

The ground-based Cherenkov telescopes have been developed under the two streams - low energy threshold and high sensitivity. The space telescopes such as EGRET can detect gamma rays in the energy region less than 10 GeV. On the other hand, ground-based Cherenkov telescopes can detect gamma rays with energy higher than sub-TeV. There is an energy gap between the satellite and ground-based detection. In the case of Imaging Atmospheric Cherenkov Telescope(IACT), the energy threshold is limited by fluctuations in the night sky light. The most straightforward method is to increase the mirror area and collects more Cherenkov photons against night sky light. CELESTE [18] and STACEE [19] are experiments using the large mirrors for solar power. MAGIC [20] is one of the next generation IACTs and they use a 17m diameter mirror.

For higher sensitivity, stereoscopic observations of Cherenkov light with multi telescopes are effective. An air shower initiated by a 1 TeV gamma ray emits a Cherenkov light pool of approximately 125m radius on the ground. The stereoscopic telescopes detect the same air shower in each place and we reconstruct the three dimensional atmospheric Cherenkov shower images. One can infer the incident direction of gamma rays (cosmic rays) more accurately and can reduce cosmic-ray background toward the source position.

The HEGRA group(La Palma, Spain) [21] is the pioneer of the stereoscopic IACTs and started observations with five small telescopes in 1997.

VERITAS [22], an Irish-UK-USA collaboration that is building an array of seven telescopes in Arizona, USA, and H.E.S.S. [23], European collabora-

Fig. 1. CANGAROO–I telescope(left) and CANGAROO–II telescope(right). Mirror diameters are 3.8m(left) and 10m(right), respectively.

tion that is building an array of initially four, and eventually 16, telescopes in Gamsberg, Namibia, are the stereoscopic observation systems with large mirrors.

3 CANGAROO–III experiment

3.1 The large steps toward stereoscopic observation

CANGAROO–III, the next phase of the CANGAROO group, aims at the detection of VHE gamma rays using four 10m diameter telescopes for stereoscopic reconstruction of atmospheric Cherenkov shower images [24](Fig. 2). The first telescope of the CANGAROO–III array is the CANGAROO–II telescope, which has been in operation since April 1999. The telescope reflector has an parabolic shape, and consists of 60(114 since March 2000) small spherical mirrors with diameter of 80cm and made of carbon-fiber reinforced plastic [25]. The first telescope was used for stand-alone observation for two years. With improved plastic mirrors, a wider field of view camera, and faster electronics and data acquisition system, we started stereoscopic observations. The second telescope was built in March 2002 and the remaining two telescopes was constructed in 2003 [26]. The recent status of mirrors, data acquisition, telescope control and camera of CANGAROO–III are reported elsewhere [27] [28] [29] [30].

The advantages of stereoscopic observation are as follows ;

- Reconstruction of the arrival direction of showers on an event-by-event basis, with good angular resolution($< 0.1°$),
- Improvement in the energy resolution of $\sim 20\%$.

The stereoscopic technique allows us to study the spatial structure of extended gamma-ray sources, such as supernova remnants.

3.2 Camera

Various improvements in the design of imaging camera have been made for the CANGAROO–III experiment [31]. The cameras of CANGAROO I, II and III

Fig. 2. CANGAROO–III Experiment(composite image). Four 10m telescopes are operated in the desert.

are compared in Fig. 3. We have chosen a wider field of view for the efficiency of stereoscopic observation [32]. But in the wide field, the chance of having bright stars within the field-of-view has increased. Therefore, the High Voltages(HVs) for the PMTs are individually controlled in order to avoid the deterioration of PMT performance by high current that bright stars cause. The comparison of the specification of CANGAROO–II and III telescope is shown in Table.1. The better dynamic range and the good light collection efficiency with Winston-cone light guide were achieved. The pixels were arranged in hexagonal shape in order to maximize the collection efficiency of the Cherenkov light. The pixel size was determined to be 0.168° from a simulation study [32], considering the spot size of the 10-m composite reflector.

Signals from the PMTs are fed into analog-buffer amplifiers. One output goes to the front-end module (discriminator and scaler) and the other goes to VME-based ADCs. The discriminated signals are sent to TDCs to measure the timing with 1-ns resolution. Timing information enable us to reject the accidental photons due to the night sky light.

The camera, mirrors and data acquisition system for the second telescope were installed in 2002 and the stereoscopic observations with the first telescope were started in December 2002. The camera is working well and we are collecting clear images of Cherenkov light.

Fig. 3. The comparison of Camera of CANGAROO–I(upper left), CANGAROO–II(upper right) and CANGAROO–III(lower).

Table 1. The comparison of imaging camera of CANGAROO–II and CANGAROO–III.

Improvement	CANGAROO–II	CANGAROO–III
Field of View	2.7°	4°
Pixels/pixel size	552/0.115°	427/0.168°
PMT	R4124UV	R3479UV
Pre-amplifier	TR402S	MAX4107
dynamic-range	20p.e	200 p.e.
HV supply	BOX unit	individual
Light guide	square	hexagonal

4 The perspective of VHE gamma-ray astronomy

4.1 Accelerators in the universe: Supernova remnants

The motivation for VHE gamma-ray astronomy is to understand where and how cosmic rays are accelerated in the universe. Cosmic rays are charged particles and are bended by the galactic magnetic field and lose the directional information before reaching the earth. Since gamma rays coming from the cosmic-ray acceleration site are not bended by the magnetic field, we can trace the sources of cosmic rays. In the vicinity of the source, accelerated cosmic rays (protons, nuclei and electrons) generate high energy gamma rays. The electrons produce low energy photons (radio to X-ray) through synchrotron radiation in the magnetic fields. The photons such as cosmic microwave background can be boosted to TeV energies by inverse Compton scattering with high energy electrons. Protons and nuclei cause strong interactions with interstellar matter, producing high energy pions. Neutral pions decay into gamma rays. The energy spectrum of gamma rays reflects the maximum energy of cosmic ray and the power-law index of cosmic rays: it is a probe of acceleration mechanisms of cosmic rays.

Supernova Remnants(SNR) are thought to be one of the cosmic-ray accelerators. Non-thermal X-rays from the rim of SNR was discovered [33] and it suggested the existence of high energy electrons in shock waves. The CANGAROO group has observed TeV gamma-ray signals from SNR SN1006 [15] [34](Fig. 4). This spectrum was well fit by the inverse Compton scattering of cosmic-ray electrons. On the other hand, SNR RXJ1713.7-3946 is different from it. This object is the same shell-type SNR that was discovered with ROSAT all sky survey and CANGAROO–I telescope [16]. But the observation with CANGAROO–II indicated the TeV gamma ray was caused by the pion decay process [35](Fig. 4). The RCW86 [36] and RXJ0852.0-4622 [37] are the shell-type SNRs that strong non-thermal X-ray was detected. the CAN-

GAROO group has observed them and the preliminary results show the possible signals of sub-TeV gamma rays. We are about to searching the origin of the cosmic rays.

We also have observed AGN in the southern sky [38] [39], pulsars [40] [41] [42], which are considered as one of the cosmic-ray accelerators.

4.2 New type objects

The CANGAROO group detected gamma rays from a normal spiral galaxy showing the starburst activities, NGC253 [43] [44]. The alpha distributions suggest the diffuse sources. The significance map are shown in Fig. 5. This is the first detection from the extragalactic objects except for AGN and the largest structure ever detected.

The center region of our galaxy is one of the most interesting region. EGRET detected a GeV gamma-ray source at the Galactic Center [45]. However, it is not yet clear that whether it is a point source or a diffuse source. Various theories have suggested for the origin of the high energy emission: the accretion disk around the massive black hole [46] or supernova remnants [47]. If the high energy radiation continues up to the sub TeV gamma-rays region or has a cut-off in the spectrum in the TeV gamma-ray region, observations with IACTs will provide important information to help determine the radiation mechanism.

On the other hand, from a point of view of particle physics, annihilation of putative dark matter neutralinos might be the origin of the gamma rays from

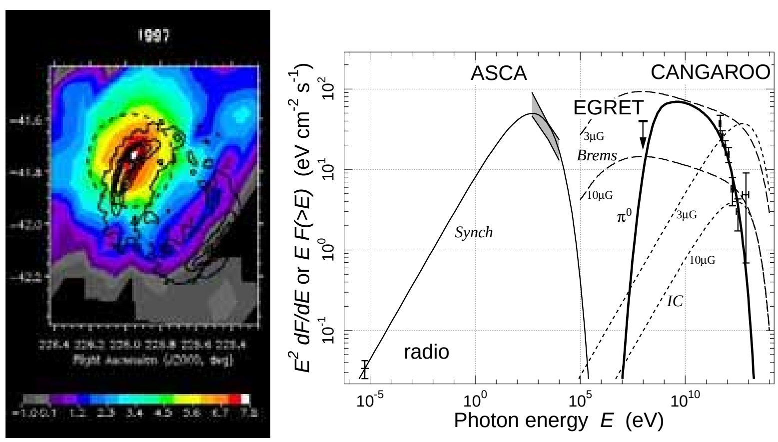

Fig. 4. (left) Contour map of statistical significance for various positions in the sky around SNR SN1006. The TeV gamma-ray emission region matches the X-ray image fairly well [15]. (right) Multi-band emission from SNR RXJ1713.7-3946 and emission models. This indicates that the TeV gamma-ray emission is caused by the pion decay process [35].

the Galactic Center. A substantial density enhancement near the center and neutralino annihilation rate larger than that predicted previously give IACTs a chance of detecting a gamma-ray signal in the 100 GeV–10 TeV region [48].

We observed the Galactic Center with the CANGAROO–II telescope for two years. The "Alpha" (image orientation angle) distributions, obtained by Likelihood analysis [49] [50], are shown in Fig. 6. The histograms were normalized by OFF-source events with $\alpha > 30°$. The observation in 2001(observation time,$\sim$50 hours) has shown a considerable excess around $\alpha \sim 0°$, possibly indicating gamma-ray signals with an energy threshold of about 400 GeV. The recent results including the 2002 data are presented elsewhere [51].

We also have observed the jet-objects [52] and an EGRET unidentified source [53], up-to-date results shows no gamma-ray signal.

The search for new gamma-ray source will give us not only new viewpoint for the origin of cosmic ray also new physics.

5 Summary

Four 10m telescopes of the CANGAROO–III experiment were constructed in 2003 and the stereoscopic observation has started. The CANGAROO–III camera is working well and we can get clean shower images. In the near future, we will be able to obtain the new knowledge about cosmic ray by the precise measurement of VHE gamma rays from the celestial objects.

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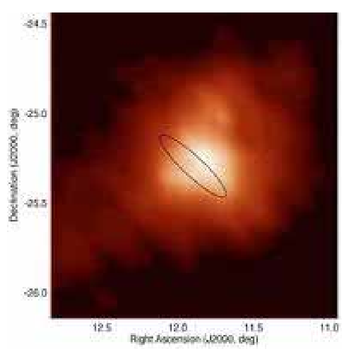

Fig. 5. Profile of the emission around NGC253 obtained by CANGAROO–II telescope. The optical image(line) is overlaid [43].

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References

1. R.A.Ong, Phys. Rep. **305**, 93 (1998)
2. C.M.Hoffman et al., Rev. Mod. Phys. Vol.**71**, No.4 (1999)
3. T.Tanimori, Prog. Theo. Phys. Suppl. No.**143**, 78 (2001)
4. T.C.Weekes: *Very High Energy Gamma-Ray Astronomy*, (Institute of Physics Publishing, Bristol and Philadelphia 2003)
5. E.Lorenz, these proceedings
6. T.Kifune and J.R.Patterson, Australian and New Zealand Physicist **29**, 58 (1992)
7. D.J.Thompson et al., Astrophys. J. Suppl. **86**, 629 (1993)
8. R.C.Hartman et al., Astrophys. J. Suppl. **123**, 79 (1999)
9. T.C.Weekes et al., Astrophys. J. **342**, 379 (1989)
10. M.Punch et al., Nature **358**, 477 (1992)
11. T.Hara et al., Nucl. Instr. Meth. **A332**, 300 (1993)
12. T.Kifune et al., Astrophys. J. Lett. **438**, L91 (1995)
13. T.Yoshikoshi et al., Astrophys. J. Lett. **487**, L65 (1997)
14. T.Sako et al., Astrophys. J. **537**, 422 (2000)
15. T.Tanimori et al., Astrophys. J. Lett. **497**, L25 (1998)

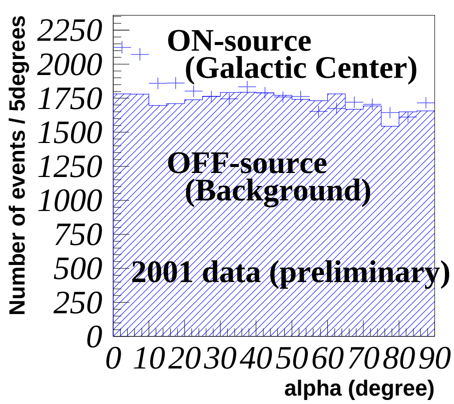

Fig. 6. Alpha(image orientation angle) distributions of the Galactic Center. On-source data is the Galactic Center and OFF-source data is the background. The excess events around 0 degree shows the gamma-ray signals from the Galactic Center.

16. H.Muraishi et al., Astronomy and Astrophysics **354**, L57 (2000)
17. A.Asahara et al., submitted to Nucl. Instr. Meth. A
18. J.Quebert et al., Towards a Major Atmospheric Cherenkov Detector IV (Padova) ed M Cresti (University of Padova) p.248 (1995)
19. M.C.Chantell et al., Nucl. Instr. Meth. **A408**, 468 (1998)
20. E.Lorenz, AIP conf. Proc. **515**, p.510 (2000)
21. A.Konoperko et al., Astropart. Phys. **10**, 275 (1999)
22. T.C.Weekes et al., Astropart. Phys. **17**, 221 (2002)
23. W.Hofmann, AIP conf. Proc. **515**, p.500 (2000)
24. M.Mori, AIP conf. Proc. **515**, p.485 (2000)
25. A.Kawachi et al., Astropart. Phys. **14**, 261 (2001)
26. R.Enomoto et al., Proc. 28th International Cosmic Ray Conference(ICRC) (Tsukuba, Japan) Vol.5, p.2807 (eds. T.Kajita et al., Universal Academy Press, Tokyo, 2003)
27. M.Ohishi et al., Proc. 28th ICRC Vol.5, p.2855 (UAP, Tokyo, 2003)
28. H.Kubo et al., Proc. 28th ICRC Vol.5, p.2863 (UAP, Tokyo, 2003)
29. S.Hayashi et al., Proc. 28th ICRC Vol.5, p.2867 (UAP, Tokyo, 2003)
30. S.Kabuki et al., Proc. 28th ICRC Vol.5, p.2859 (UAP, Tokyo, 2003)
31. S.Kabuki et al., Nucl. Instr. Meth. **A500**, 318 (2003)
32. R.Enomoto et al., Astropart. Phys. **16**, 235 (2002)
33. K.Koyama et al., Nature **376**, 255 (1995)
34. S.Hara et al., Proc. 27th ICRC (Hamburg, Germany) Vol.5, p.2455 (Copernicus Gesellshaft, eds. M.Simon, E.Lorenz and M.Pohl, 2001)
35. R.Enomoto et al., Nature **416**, 823 (2002)
36. S.Watanabe et al., Proc. 28th ICRC Vol.4, p.2397 (UAP, Tokyo, 2003)
37. H.Katagiri et al., Proc. 28th ICRC Vol.4, p.2409 (UAP, Tokyo, 2003)
38. K.Okumura et al., Astrophys. J. Lett. **579**, L9 (2002)
39. T.Nakase et al., Proc. 28th ICRC Vol.5, p.2587 (UAP, Tokyo, 2003)
40. J.Kushida et al., Proc. 28th ICRC Vol.4, p.2493 (UAP, Tokyo, 2003)
41. D.Nishida et al., Proc. 28th ICRC Vol.4, p.2489 (UAP, Tokyo, 2003)
42. A.Kawachi et al, submitted to Astrophys. J.
43. C.Itoh et al., Astronomy and Astrophysics **396**, L1 (2002)
44. C.Itoh et al., Astrophys. J. Lett. **584**, L65 (2003)
45. H.A.Mayer-Hasselwander et al., Astronomy and Astrophysics **335**, 161 (1998)
46. R.Mahadevan et al., Astrophys. J. Lett. **486**, 268 (1997)
47. F.Melia et al., Astrophys. J. Lett. **508**, L65 (1998)
48. L.Bergström et al., Astropart. Phys. **9**, 137 (1998)
49. R.Enomoto et al., Proc. 27th ICRC Vol.5, p.2477 (2001)
50. C.Itoh et al., Astronomy and Astrophysics **402**, 443 (2003)
51. K.Tsuchiya et al., Proc. 28th ICRC Vol.4, p.2517 (UAP, Tokyo, 2003)
52. S.Hayashi et al., Proc. 28th ICRC Vol.4, p.2533 (UAP, Tokyo, 2003)
53. T.Hattori et al., Proc. 28th ICRC Vol.5, p.2659 (UAP, Tokyo, 2003)