Status of the CANGAROO-III Project

H. Kubo [a], A. Asahara [a], G.V. Bicknell [b], R.W. Clay [c], Y. Doi [d], P.G. Edwards [e], R. Enomoto [f], S. Gunji [d], S. Hara [f], T. Hara [g], T. Hattori [h], Sei. Hayashi [i], C. Itoh [j], S. Kabuki [f], F. Kajino [i], H. Katagiri [f], A. Kawachi [f], T. Kifune [k], L.T. Ksenofontov [f], T. Kurihara [h], R. Kurosaka [f], J. Kushida [h], Y. Matsubara [ℓ], Y. Miyashita [h], Y. Mizumoto [m], M. Mori [f], H. Moro [h], H. Muraishi [n], Y. Muraki [ℓ], T. Naito [g], T. Nakase [h], D. Nishida [a], K. Nishijima [h], M. Ohishi [f], K. Okumura [f], J.R. Patterson [c], R.J. Protheroe [c], N. Sakamoto [d], K. Sakurazawa [o], D.L. Swaby [c], T. Tanimori [a], H. Tanimura [a], G. Thornton [c], F. Tokanai [d], K. Tsuchiya [f], T. Uchida [f], S. Watanabe [a], T. Yamaoka [i], S. Yanagita [p], T. Yoshida [p], T. Yoshikoshi [q]

[a] *Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan*

[b] *Australian National University, ACT 2611, Australia*

[c] *University of Adelaide, SA 5005, Australia*

[d] *Yamagata University, Yamagata, Yamagata 990-8560, Japan*

[e] *Inst. Space and Astronautical Science, Sagamihara, Kanagawa 229-8510, Japan*

[f] *Inst. for Cosmic Ray Research, Univ. of Tokyo, Kashiwa, Chiba 277-8582, Japan*

[g] *Yamanashi Gakuin University, Kofu, Yamanashi 400-8575, Japan*

[h] *Tokai University, Hiratsuka, Kanagawa 259-1292, Japan*

[i] *Konan University, Kobe, Hyogo 658-8501, Japan*

[j] *Ibaraki Prefectural Univ. of Health Sciences, Ami, Ibaraki 300-0394, Japan*

[k] *Shinshu University, Nagano, Nagano 480-8553, Japan*

[ℓ] *STE Laboratory, Nagoya University, Nagoya, Aichi 464-8602, Japan*

[m] *National Astronomical Observatory of Japan, Tokyo 181-8588, Japan*

[n] *Kitasato University, Sagamihara, Kanagawa 228-8555, Japan*

[o] *Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan*

[p] *Ibaraki University, Mito, Ibaraki 310-8512, Japan*

[q] *Osaka City University, Osaka, Osaka 558-8585, Japan*

Abstract

The CANGAROO-III project, which will consist of an array of four 10 m atmospheric Cherenkov telescopes for gamma-ray astrophysics, started in 1999 in Woomera, South Australia. The first 10 m telescope has been in operation since 2000, and stereoscopic observations with the first and second telescopes started in 2002. The full array will be operational in 2003. Here we report on the status of the CANGAROO-III project including the results of observations with the first telescope.

Key words: TeV gamma-ray; Imaging atmospheric Cherenkov telescope

1 Introduction

CANGAROO-III is a project to study celestial gamma-rays in the 100 GeV region utilizing stereoscopic observations of Cherenkov light with an array of four 10 m Imaging Atmospheric Cherenkov Telescopes (IACTs) (25), following the CANGAROO-I 3.8 m (7) and CANGAROO-II 7 m (34) telescopes in Woomera, South Australia (136°47'E, 31°06'S, 160m a.s.l.). The construction of the CANGAROO-III telescopes started in April 1999 and it is initially planned as a five-year program. In March 2000 the 7 m telescope was expanded to 10 m to become the first telescope of the CANGAROO-III array (Fig. 1). The second telescope has been in operation since December 2002. The third and fourth ones will be completed in 2003.

A simulation study shows that by intersecting the major axes of images observed by multiple telescopes separated by about 100 m, the angular resolution for gamma-rays is improved to 0.15° (RMS) at 0.5 TeV per shower (4), which is better than 0.23° (RMS) above 0.5 TeV obtained with the single telescope observation for one month (12). Furthermore, by knowing the distance to the shower core the gamma-ray energy resolution is expected to be 10–15% (RMS) for stereo observations compared with 30–40% (RMS) for the single telescope case (39).

2 The First 10 m Telescope

2.1 Design

The CANGAROO-III 10 m reflector has a focal length of 8 m with a parabolic design in order to keep the synchronicity of arrival times of Cherenkov photons within a few ns. The surface is tessellated with 114 spherical mirror facets of 80 cm diameter, with an effective light collecting area of 57 m^2. For the base material of the mirror, Carbon Fiber Reinforced Plastic (CFRP) is used, which is the first case for an IACT. It weighs about one-third of a glass mirror, resulting in reduced gravitational deformation (17). The orientation of each mirror is remotely adjusted by stepping motors. The image of a star measured with a CCD camera was found to be spread over 0.20° (FWHM).

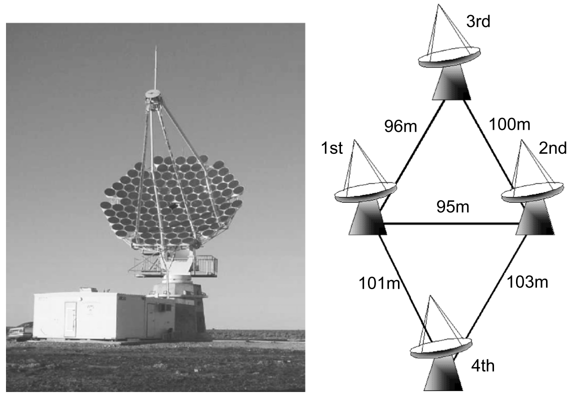

Fig. 1. CANGAROO-III first 10m telescope (left) and the arrangement of four telescopes (right).

The camera consists of 552 PMTs of half-inch diameter with light-collecting cones to reduce the dead space between the photosensitive area of the PMTs. It covers a field of view of about 3 degrees. Signals from the PMTs are fed into analog-buffer amplifiers. One output goes to a custom-made front-end module (discriminator and scaler) and the other goes to a VME-based charge-integrated ADC with 12 bit resolution. The discriminated signals are sent to TDCs to measure timing with 1 ns resolution, which enables us to reject almost all the photons due to the night sky background. These event data are collected by a CPU (running Linux) and stored in a disk with house-keeping data such as that from a cloud monitor which detects far infrared light to monitor the sky condition.

From simulations, the energy threshold for gamma-rays with zenith angle $\sim 10^\circ$ is estimated to be $\sim$500 GeV and $\sim$400 GeV for $E^{-2.5}$ and $E^{-3.0}$ spectra respectively (11), while that of cosmic rays is estimated to be 800 GeV (2).

2.2 Observations and Results

Table 1 lists the objects observed with the first 10 m telescope from March 2000 to April 2003. The results are briefly described below, and observed energy spectra are shown in Fig. 2.

Supernova Remnants The shock waves in supernova remnants (SNRs) are long considered to be the most promising accelerator of galactic cosmic rays up to energies around 10^{15} eV. We have been observing SNRs from which non-thermal X-ray emissions have been detected, which imply the presence of high energy particles. The first SNR detected at TeV gamma-ray energies was SN1006, following the detection of non-thermal X-ray emission from the SNR rims with *ASCA* (20). TeV gamma-rays from the north-eastern rim were detected with the CANGAROO-I 3.8 m telescope (33) and confirmed with the first 10 m telescope (6). The observed TeV spectrum was represented well by a model of inverse Compton scattering of high energy electrons with the 2.7 K cosmic microwave background (CMB), while the emission from radio to X-ray bands is synchrotron radiation in the magnetic field of 4μG (33; 27). RX J1713.7−3946 is the second example of a shell type SNR with non-thermal X-ray emission. As expected from theoretical considerations, TeV gamma-rays were detected with the CANGAROO-I telescope from the northwest rim (26; 21), and confirmed with the first 10 m telescope (3). The observed spectrum resembled a single power law down to 0.4 TeV, which was best fitted with the spectrum of neither inverse Compton scattering nor bremsstrahlung, but rather pion decay production. If confirmed, it would be the first evidence of proton acceleration in SNRs, and supports the SNR origin of cosmic rays. However, taking account of a nearby EGRET unidentified source it is difficult to make a fit by a simple power-law pion-derived spectrum. Further stereo observations with higher angular resolution are necessary to settle the controversy. RX J0852.0−4622 and RCW86, both of which are shell-type SNRs in the southern hemisphere, have been observed, with the first 10 m telescope pointed to the position where the non-thermal X-ray emissions detected with *ASCA* had the maximum intensity (16; 38). Both analyses are continuing.

Pulsar Nebulae Rotation powered pulsars lose a large amount of energy with rotational deceleration, and part of the energy is used for the acceleration of radiating particles. Pulsed emission from seven pulsars was detected with the EGRET detector on board the *CGRO* satellite (35; 15). However, no pulsed emission has been detected in the TeV band. Therefore it has been proposed that the shock front in the nebula accelerates particles, and TeV gamma-rays are emitted via inverse Compton scattering by high energy electrons. We have observed pulsars/nebulae with higher spin-down energies. The Crab pulsar is the first rank, and a "standard candle" in the TeV band. However, the large zenith angles from the CANGAROO-III site raise the gamma-ray energy threshold up to ∼2 TeV. The observed spectrum with the first 10 m telescope is consistent with results from CANGAROO-I and HEGRA (11), which shows our energy and flux estimations are correct. Pulsars with higher spin-down energies — Vela, PSR B1706−44, and PSR B1509−58 — have been observed with the first 10 m telescope. Unpulsed TeV gamma-ray emission from PSR B1706−44 was detected with the CANGAROO-I telescope (19), and confirmed with the first 10 m telescope (24). However, the spectral index seems to change around 1 TeV and becomes flatter at lower energies. A recent *Chandra* observation revealed a compact nebula, and the X-ray spectrum indicates that the synchrotron peak energy appears to be above 10 keV. These results show that TeV emission can not be explained by the conventional model assuming inverse Compton scattering of the 2.7 K CMB (24). PSR J1420−6048, a recently discovered pulsar with a large spin-down energy which is comparable to those of the pulsars mentioned above (29), has been added to the target list.

Other Galactic sources A binary system of a pulsar and Be star, PSR B1259−63/SS 2883, was observed with the first 10 m telescope, and the obtained upper limits constrain the outflow parameters of the Be star (18). We have observed the Galactic center Sgr A*, which may produce gamma-ray emission from the accretion disk around the massive black hole, and SS433, which is a micro-quasar with a bipolar jet. Both analyses are on-going (36; 9).

Blazars (HBLs) Blazars, the generic term for BL Lacertae objects and flat-spectrum radio quasars, show highly variable non-thermal emission from radio to gamma-ray bands. HBLs, defined as BL Lac objects with high peak energy of synchrotron radiation, are candidate TeV emitters because all the BL Lacs detected so far in the TeV gamma-ray region are HBLs. TeV gamma-rays from BL Lacs can be used as a probe of the intergalactic infrared radiation field (IIRF) as they are absorbed due to pair creation. Mrk421 is a nearby HBL which has been detected with many IACTs in the northern hemisphere. We observed it with the first 10 m telescope during the flaring state in 2001. It was detected at 5.7 σ above 10 TeV, and a 4σ excess above 20 TeV favors a cutoff energy of $\sim$8 TeV (32). This will provide strong constraints on the poorly known IIRF spectrum. We also observed PKS2005−489 and PKS2155−304 with the first 10 m telescope, and upper limits were obtained (28). In 2000 we observed these two objects simultaneously with *RXTE*, and the results will be reported elsewhere (37).

Other extra-galactic sources NGC 253 is a normal spiral galaxy showing starburst activity. The detection, with the first 10 m telescope, indicated the possible extension of the TeV gamma-ray emission region (10; 12). This suggests many interesting possibilities (11) and we need to measure the angular extent with stereo observations. 3EG J1234−1318 is one of the seven steady EGRET unidentified sources at high Galactic latitude, which has been suggested to be due to a merger of clusters of galaxies. The detection of synchrotron emission from clusters of galaxies at radio, EUV and hard X-ray energies indicates the presence of high energy particles. We have observed it with the first 10 m telescope, and the data are under analysis (8).

3 Status of CANGAROO-III

The second telescope was constructed in early 2000 with many improvements described below. The cosmic ray energy threshold was estimated to be about 320 GeV, which is a factor of 2.5 better than the first telescope (14).

Reflector The reflector design is the almost same as the first 10 m telescope. Glass FRP is adopted instead of the Carbon FRP, which raises the rigidity of the mirror (31). The spot-size of the reflector was measured to be 0.21° (FWHM). Further fine tuning should decrease the size to 0.18°.

Camera The new imaging camera has a hexagonal design to minimize the dead space between PMTs (13). The total field of view of about 4° is covered by 427 PMTs of 3/4″ diameter. The light guides have been redesigned to

Table 1
Objects observed with the CANGAROO-III telescope from March 2000 to April 2003.

Object†	d	ON-source obs. (hr)‡				Status♯	Ref.
	(kpc)	2000	'01	'02	'03		
RXJ 0852.0−4622[a]	0.5	-	-	41	51	A	(16)
SN1006[a] (NE rim)	2	52	33	-	43	D*	(6)
RCW86[a] (SW shell)	3 (1)	-	38	41	65	A	(38)
RX J1713.7−3946[a]	6 (1)	-	24	44	-	D*	(3)
SN1987A[a]	50	-	21	-	-	U	(5; 22)
Vela[b]	0.25	12	39	38	-	A	
PSR B1706−44[b]	1.8	32	31	-	-	D*	(24)
Crab[b]	2.0	55	-	-	-	D*	(12)
PSR 1509−58[b]	4.2	-	-	35	-	A	
PSR J1420−6048[b]	7.7 (2)	-	-	26	-	A	(29)
PSR 1259−63[c]	1.5	3	18	-	-	U	(18)
SS 433[d] (W lobe)	5	-	51	34	-	A	(9)
Sgr A* [e]	8	-	52	82	-	A	(36)
SMC[f]	64	-	-	41	-	A	
NGC 253[g]	2.5 Mpc	38	43	-	-	D	(10; 11; 12)
Mrk 421[h]	$z = 0.031$	-	18	9	6	D	(32; 28)
EXO 0556.4−3838[h]	$z = 0.034$	-	-	21	15	A	(28)
PKS 0548−322[h]	$z = 0.069$	3	-	-	-	A	
PKS 2005−489[h]	$z = 0.071$	33	-	-	-	U	(28; 37)
PKS 2155−304[h]	$z = 0.116$	36	29	-	-	U	(28; 37)
3EG J1234−1318[i]	-	-	-	23	-	A	(8)

† [a]SNR, [b]pulsar/nebula, [c]pulsar/Be star binary, [d]micro quasar, [e]Galactic center, [f]galaxy in the Local Group, [g]starburst galaxy, [h]blazar(HBL), [i]EGRET unidentified. ‡ Bad weather runs are included. From 2000 to 2002 they were taken with a single telescope, while stereo observations have been conducted in 2003. Each observation time of OFF-source runs is roughly the same as ON-source runs. ♯ A:Under analysis, D:Detected with a statistical significance exceeding 5 standard deviations, and furthermore the * symbol shows double detections with the CANGAROO-III and CANGAROO-I 3.8 m telescopes, U:Upper limit obtained.

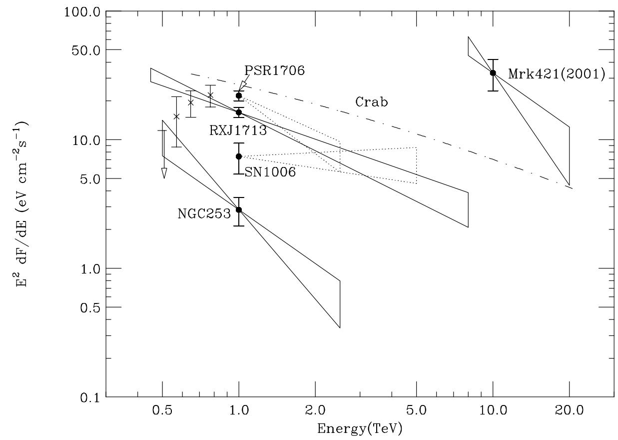

Fig. 2. Energy spectra observed with the first 10 m telescope of CANGAROO-III. Only statistical errors are shown. For PSR B1706−44 cross symbols and an upper limit are plotted below 1 TeV. The dot-dash line is that of the Crab nebula for a reference (1).

maximize photon collection for the new hexagonal arrangement. High voltages are supplied to PMTs individually. Each PMT base includes a preamplifier, and signals are transmitted via twisted cables to the electronics installed on the verandah of the telescope. The linearity is maintained up to about 200 p.e. and the dynamic range after software correction is ∼250 p.e.

Electronics The new electronics are all based on the VME specification in order to speed up the readout time (23). The DAQ system can accept triggers at a rate of 350 Hz with a dead time of 20%. A pattern trigger circuit using a Programmable Logic Device is under development to decrease accidental triggers due to night sky background photons (30). The DAQ systems of the first and second telescopes are triggered by shower events individually. Stereo shower events are reconstructed in the off-line analysis.

The stereoscopic observation with the first and second 10 m telescopes started in December 2002. The objects observed with two telescopes are listed in Table 1. The stereo events have been obtained at a rate of a few Hz, which shows that the energy threshold of stereoscopic observations depends on that of the first telescope. The detailed performance is under analysis. The frame of the third telescope was completed in late 2002. Installation of mirrors and electronics, and construction of the fourth telescope frame, will be completed in July 2003. All four telescopes will be operational at the end of 2003.

4 Summary

The CANGAROO-III project to search for high energy gamma-ray objects in the southern hemisphere with an array of four 10m IACTs began in 1999. With the first telescope we revisited the SNRs and pulsar nebulae detected with the

CANGAROO-I 3.8 m telescope, and confirmed detections with lower energy threshold. In addition a blazar and a starburst galaxy have been detected. Stereo observations with two telescopes started in December 2002. The full array will be completed in 2003. We will explore the gamma-ray sky above 0.1 TeV with an angular resolution of less than 0.1 degree.

Acknowledgements

This project was supported by a Grant-in-Aid for Scientific Research of the Ministry of Education, Culture, Science, Sports and Technology of Japan and the Australian Research Council. The receipt of JSPS Research Fellowships is also acknowledged. We thank DSC Woomera for their assistance in constructing the telescopes.

References

[1] Aharonian, F. A. et al., 2000, ApJ, 539, 317
[2] Asahara, A. et al., 2003, submitted to Nucl. Instr. and Meth. A
[3] Enomoto, R. et al., 2002, Nature, 416, 823
[4] Enomoto, R. et al., 2002, Astropart. Phys., 16, 235
[5] Enomoto, R. et al., 2003, ApJ, 591, L25
[6] Hara, S., 2002, PhD thesis, Tokyo Inst. Tech.
[7] Hara, T. et al., 1993, Nucl. Instr. and Meth. A, 332, 300
[8] Hattori, T. et al., 2003, in Proc. 28th ICRC (Tsukuba), 2659, http://www-rccn.icrr.u-tokyo.ac.jp/icrc2003/proceedings_pdf.html
[9] Hayashi, Sei. et al., 2003, in Proc. 28th ICRC, 2533
[10] Itoh, C. et al., 2002, A&A, 396, L1
[11] Itoh, C. et al., 2003, ApJ, 584, L65
[12] Itoh, C. et al., 2003, A&A, 402, 443
[13] Kabuki, S et al., 2003, Nucl. Instr. and Meth. A, 500, 318
[14] Kabuki, S et al., 2003, in Proc. 28th ICRC, 2859
[15] Kaspi, V.M. et al., 2000, ApJ, 528, 445
[16] Katagiri, H. et al., 2003, in Proc. 28th ICRC, 2409
[17] Kawachi, A. et al., 2001, Astropart. Phys., 14, 261
[18] Kawachi, A. et al., 2003, submitted to ApJ
[19] Kifune, T. et al., 1995, ApJ, 438, L91
[20] Koyama, K. et al., 1995, Nature, 378, 255
[21] Koyama, K. et al., 1997, PASJ, 49, L7
[22] Ksenofontov, L. T. et al., these proceedings
[23] Kubo, H. et al., 2001, in Proc. 27th ICRC (Hamburg), 5, 2900
[24] Kushida, J. et al., 2003, in Proc. 28th ICRC, 2493
[25] Mori, M. et al., 2000, AIP Conf. Proc. 515, 485
[26] Muraishi, H. et al., 2000, A&A, 354, L57
[27] Naito, T. et al., 1999, Astron. Nachr., 320, 205
[28] Nakase, T. et al., 2003, in Proc. 28th ICRC, 2587
[29] Nishida, D. et al., 2003, in Proc. 28th ICRC, 2489
[30] Nishijima, K. et al., 2003, in Proc. *The Universe Viewed in Gamma-Rays* (Kashiwa), Universal Academy Press, 433

[31] Ohishi, M. et al., 2003, in Proc. 28th ICRC, 2855
[32] Okumura, K. et al., 2002, ApJ, 579, L9
[33] Tanimori, T. et al., 1998, ApJ, 492, L33
[34] Tanimori, T. et al., 1999, Proc. 26th ICRC (Salt Lake City), 5, 203
[35] Thompson, D.J. et al., 1999, ApJ, 516, 297
[36] Tsuchiya, K. et al., 2003, in Proc. 28th ICRC, 2517
[37] Urry, M. et al., in preparation
[38] Watanabe, S. et al., 2003, in Proc. 28th ICRC, 2397
[39] Weekes, T. C. 2003, "Very High Energy Gamma-ray Astronomy", Institute of Physics Publishing