CANGAROO Project for High-Energy Gamma-Ray Astrophysics

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Astrophyisical motivations, recent status and results from the international CANGAROO project in Woomera, South Australia are described. Since 1990, with ground-based gamma-ray telecopes using the imaging Cherenkov technique, we are exploring the high-energy phenomena in the Universe and providing new insights to active and extreme astrophysical objects by its observational data at the highest end of photon spectrum.

§1. Introduction

CANGAROO is an acronym for Collaboration between Australia and Nippon (Japan) for a Gamma-Ray Observatory in the Outback. We started this international project in 1990 with a 3.8m telescope originally developed for lunar ranging, and we equipped it with a fine-resolution Cherenkov imaging camera.[1] Now an array of four 10m Cherenkov telescopes are to be ready in 2003 for high-sensitive detection of high-energy gamma-rays in Woomera, South Australia. We have discovered new gamma-ray objects in the southern sky with unprecedented sensitivity as the first imaging atmospheric telescope in the southern hemisphere. Astrophysical motivations and major discoveries by CANGAROO are described in this article.

§2. High-energy gamma-ray astronomy

The highest energy end of the photon spectrum is the last frontier of astronomy.**) In general, expected number of photons decreases with energy and the statistics is the most crucial problem in gamma-ray astrophysics. The earth atmosphere is not transparent for gamma-rays and satellites are the only possible gamma-ray observatories about a decade ago. The detection area of space-based gamma-ray detectors is limited in size of satellites, 1 m^2 or so, and this determines the practical upper limit of detectable gamma-ray energy.

Figure 1 shows the skymap of gamma-rays above 100 MeV observed by EGRET aboard the Compton Gamma Ray Observatory launched in 1991.***) The galactic plane is prominent. A total of 271 point sources were detected[2] but many of them

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**) In this article, we concentrate on high-energy gamma-rays above several MeV, omitting the energy region dominated by nuclear level transition processes.

***) http://lheawww.gsfc.nasa.gov/docs/gamcosray/EGRET/egret.html

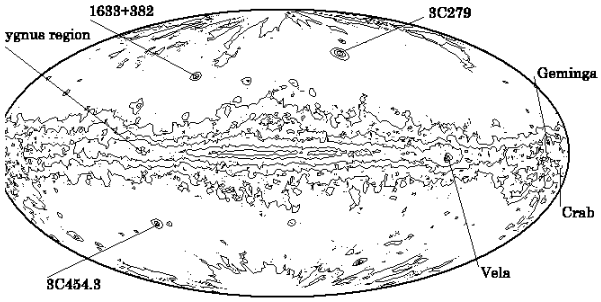

Fig. 1. GeV gamma-ray skymap observed by EGRET. The plot represents a celestial sphere in galactic coordinates. Contours show gamma-ray intensities above 100 MeV.

Table I. GeV gamma-ray sources classified by their object types.[2)]

Pulsars	5
AGN (mostly blazars)	66 27 (marginal)
Radio galaxy (Cen Z)	1 (marginal)
Unidentified (Some may be SNRs)	170
Large Magellanic Cloud	1
Solar flare	1
Total	271

are unidentified sources due to the limited angular resolution of the detector. Table I is the summary of source types detected by EGRET.

2.1. *Gamma-ray production mechanism*

There are four basic process for gamma-ray production above several MeV.[3)] Note that these are all non-thermal processes.

- Synchrotron emission: Energetic electrons emits gamma-rays in magnetic fields.
- Inverse Compton scattering: Energetic electrons up-scatter ambent low energy photons to higher energies.
- Bremsstrahlung: Energetic electrons emits gamma-rays when encountered with atomic Coulomb fields.
- Neutral pion decay: Energetic protons produce neutral pions when collide with nuclei and neutral pions decay into gamma-rays promptly.

In any case, high-energy gamma-rays are produced by charged particles accelerated to high energies in the astrophysical environment. Therefore the long-standing mystery of the origin of high-energy cosmic-rays is closely related to gamma-rays. Astrophysical objects emitting gamma-rays should also be the source of cosmic-rays. In other words, astrophysical objects which produce cosmic rays can be explored only by gamma-rays since the Galactic magnetic fields prevent charged cosmic rays from traveling straight in the Galaxy.

2.2. *Cherenkov telescope*

High-energy gamma-rays bombarding the earth atmosphere create electron-positron pairs in the electromagnetic field of atoms, and these secondary particles produce gamma-rays via bremsstrahlung in the atomic Coulomb fields, which create pairs again. Thus electromagnetic cascade showers develops until the average particle energy becomes lower than matter-specific critical energy (21 MeV in the case of electrons in the atmosphere.) If the primary energy of a gamma-ray is high enough, the shower particles can reach the ground and can be detected by particle detector arrays. However, even if the shower declines high in the atmosphere, we can detect Cherenkov radiation emitted by charged particles in the shower. With the refractive index, n, of about 1.0003 (STP) of atmosphere, the emission angle of Cherenkov light is $\theta = \cos^{-1}(1/n\beta) = 1.3^{\circ}$ (where $\beta = v/c$ is the velocity of a charged particle in unit of light velocity) or even smaller in the upper atmosphere, which retains directional information of the primary gamma-ray. The Cherenkov photons emitted by showers come to ground as a disk of about 300m in diameter and a few meter in thickness. This size of Cherenkov light pool enables us to detect such light in large detection area of order 10^5 m^2. This is why we can detect high-energy gamma-rays from ground telescopes even its flux is low.[4)]

2.3. *Imaging method*

There is, however, a further difficulty in detection of gamma-ray showers from ground. Cosmic-rays, high-energy protons and nuclei bombarding the earth, produce Cherenkov light far more frequently in the earth atmosphere. Until the imaging method, which I will explain later, was realized with the advance of technology, distinguishing gamma-ray showers from cosmic-ray showers by Cherenkov observation had not been successful for more than about 25 years since the first trial in 1960's.[5)]

Cosmic-ray showers are initiated by nuclear interaction of cosmic-ray protons or nuclei with atmospheric nuclei. The nuclear interaction produces mainly pions. Neutral pions decay promptly into two gamma-rays and develops electromagnetic showers. Charged pions interact atmospheric nuclei again and develops nuclear cascades. Transverse momenta of secondary pions produced in nuclear interactions are rather large and cosmic-ray showers are more diffuse than gamma-ray showers in general. The idea of the imaging Cherenkov telescope was proposed in late 1970's.[6)] Later, Hillas[7)] developed a method to discriminate gamma-ray showers from cosmic-ray showers using this difference of Cherenkov light image quantitatively: he defined characteristic parameters called length, width, distance, concentration and showed the difference in distribution of these image parameters can be used to select gamma-ray showers from huge number of background cosmic-ray showers statistically, even though it is hard to distinguish gamma-ray showers from cosmic-ray showers individually.

The Crab nebula was detected at high significance by the Whipple group in 1989[8)] using this imaging technique. After this breakthrough, many groups detected this source repeatedly and the Crab is now called as a "standard candle" of the ground-based gamma-ray astronomy.

Then, image orientation angle toward the assumed source, or α, has been introduced as another effective image parameter.[9),10)] A gamma-ray signal appears as an excess events near $\alpha = 0^{\circ}$ of its distribution and this is now the standard parameter used in analysis of data acquired with single Cherenkov telescope. The first demonstration of this method was the discovery of the first extragalactic TeV gamma-ray object, Mrk 421, in 1992.[11)]

Figure 2 shows the "TeV gamma-ray sky" in 2002, which is the summary of

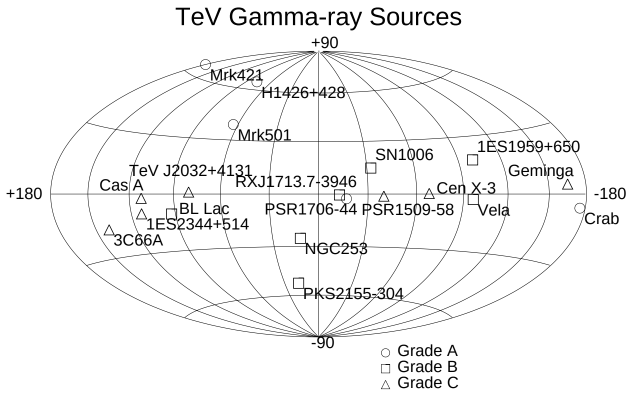

Fig. 2. TeV gamma-ray sky in 2002.

Table II. TeV gamma-ray sources classified by their object types.

4 Pulsar nebulae	Crab, Vela, PSR 1706-44, PSR 1509-58
8 blazars	Mrk 421, Mrk501, 1ES 2344+514, PKS 2155-304, 1H 1426+428, 1ES 1959+65, 3C66A, BL Lac
3 Supernova remnants	SN1006, RX J1713.7-3946, Cas A
1 X-ray binary	Cen X-3
1 Starburst galaxy	NGC253
2 Unidentified	TeV J2032+4131, Geminga

claimed sources. Now the number of sources has increased to more than ten and can be classified into Table II.

2.4. *Pulsar nebula*

Magnetized fast-rotating pulsars are cosmic power generators and observed deceleration of rotation speed implies large loss of rotational energy. If a fraction of this power is used for particle acceleration, these pulsars could be detectable at gamma-ray energies. The EGRET detector onboard the Compton Gamma Ray observatory reports six pulsars identified with rotation frequency at other wavelength.[12)] These are the natural candidates for TeV gamma-ray emitters. However, no pulsating gamma-rays are detected for the Crab nebula nor other pulsars at TeV energies. TeV emission is interpreted as coming from outside the co-rotating light cylinder of pulsars. The particle flux from the pulsar, or pulsar wind, pressing ambient ejecta or interstellar matter, produces shock front where charged particles are supposed to be accelerated by the well-known first-order Fermi mechanism may emit gamma-rays via mechanisms already explained. In the case of the Crab nebula, two broad peaks evident in the multiwavelength (radio to high-energy gamma-ray) energy spectrum can be well understood as a synchrotron peak and an inverse Compton peak derived from the same electron population producing synchrotron emission.[13)]

2.5. *Blazars*

Most of identified point source in the EGERT catalog are this kind of active galactic nuclei. It is supposed that jets from blazars are oriented toward the earth and relativistic beaming effect help to push up photons to high energies. The central engine of blazars should be massive black holes. Gravitational energy liberated from matter accretion around black holes are believed to be the source of their power. Particles in jets and those accelerated in termination shocks formed by jets could produce copious gamma-rays reaching the earth even after traveling over cosmological distances.[14] There is, however, a mechanism which attenuates the flux of multi-TeV photons emitted by extragalactic sources with redshift larger than about 0.1: TeV-photons are lost by electron-positron pair creation interacting with infrared background radiation.[15)–17] Large Cherenkov telescopes under construction will enable to increase the number of detectable blazars significantly with lower energy threshold to avoid this absorption.

2.6. *Supernova remnants*

Supernova remnants (SNRs) are assumed be the most promising origin of cosmic rays for a long time with no conclusive evidences. From the energetics argument, only a small fraction of the large amount of energy ejected at the time of supernova explosion is enough to explain the observed energy density of cosmic rays. Ejecta from explosions form shocks in collision with ambient matter, and those shocks may accelerate particles to high energy, thus producing gamma-rays.[18),19] However, finite angular resolution of EGRET has a limited capability to identify SNRs as some of their unidentified gamma-ray sources.[20] Most SNRs are distributed along the galactic plane where diffuse gamma-ray emission is dominant and clear identification was difficult. Cherenkov telescopes have better angular resolution than EGRET and can explore higher energy region, thus could be a better tool to study the cosmic ray origin which shows single power-law energy spectrum up to around 10^{15} eV, where the spectrum steepens (which is known as “knee”).

§3. CANGAROO

3.1. *Precursor – JANZOS*

Without the explosion of SN1987A we might not start the CANGAROO project. Some theories predicted a possible strong flux of gamma-rays could be emitted powered by the newly-born fast rotating pulsar which should be formed by the supernova and the flux might peak around several months after the explosion. The enthusiasm toward this rare occasion prompted to start new experiments in southern hemisphere. One of such projects was the JANZOS (Japan, New Zealand, Australia Observation of SN1987A) collaboration which aimed to construct a surface airshower detector array on a mountain, Black Birch, in South Island of New Zealand.[21),22] Shortly after construction of the array, which aimed to search for 100 TeV gamma-rays, three Cherenkov telescopes equipped with fixed reflectors of 2m in diameter were built to search for TeV gamma-rays. These telescopes observed Cherenkov light from SN1987A in drift scan mode and coincidence between three telescopes were used to reduce nightsky background events. A possible flare of TeV gamma-rays was reported,[23] but observations suffered from mountain weather. Weather in New Zealand is wet, and clear nights are rather rare. It was not a good place for Cherenkov telescopes.

3.2. *CANGAROO*

While the JANZOS project was going on, Prof. H. Hasegawa, Kyoto University, suggested the use of a former lunar ranging telescope of 3.8m diameter located in Dodaira Observatory of Tokyo Astronomical Observatory as a Cherenkov telescope. Thus Prof. Tadashi Kifune, ICRR, University of Tokyo, started to search for a better place to set this telescope for Cherenkov observation, and decided to set the 3.8m telescope in Woomera in collaboration with Dr. John Patterson, University of Adelaide (Fig. 3). Woomera is a former rocket range used by a joint project between Europe and Australia and is at the outskirt of a large prohibited area. High-voltage power lines and other infra-structure and local support were available. Adelaide group was operating a Cherenkov telescope called BIGRAT (BIcentinal Gamma Ray Telescope)[24] at that time in Woomera and had solid experience. The project was named CANGAROO (Collaboration between Australia and Nippon (Japan) for a GAmma Ray Observatory in the Outback).[1] Major events of CANGAROO are summarized in Table III.

Fig. 3. CANGAROO 3.8m telescope.

The design of the 3.8m telescope was old and they had to replace the motor drives and the computer control system. Also they had to build a Cherenkov imag-

Table III. CANGAROO chronicle.

1987	SN1987A exploded in the LMC and JANZOS group was formed.
1990	The 3.8m telescope was transferred to ICRR.
1990	ICRR-Dept. Phys. Math. Phys. , Univ. Adelaide agreement.
1992	Start observation of a 3.8m telescope.
1994	PSR 1706-44 was detected.
1995	Construction of a new telescope was approved.
1998	SN1006 was detected.
1999	CANGAROO-II 7m telescope was competed.
1999	CANGAROO-III project started.
2000	The 7m telescope was upgraded to a 10m diameter.
2001	Univ. Tokyo-Univ. Adelaide agreement.
2002	Constructions of second and third 10m telescopes.

ing camera. The new camera, set at the prime focus of the telescope, consisted of 220 photomultiplier tubes of 3/8" diameter. Electronics and data taking system for the camera were prepared for this telescope, which include front-end signal processing electronics with timing and pulse height measurement, and a VME-based single board computer was used for data acquisition with help of the online group of National Laboratory for High Energy Physics, Japan.[25]

3.3. *PSR1706-44*

An effort for a few years of struggling time to start a new experiment was awarded by the detection of gamma-ray signal from one of the gamma-ray pulsar detected in the GeV region, PSR 1706-44. This pulsar was the third most powerful one in EGRET-detected pulsars when ranked in $\dot{E}/d^2$, where $\dot{E}$ is the rotational energy loss and d is the distance. (Other two are the Crab and the Vela pulsars.)

By applying imaging analysis to shower images obtained by the highest resolution camera in the world at that time, image orientation angle, α, distribution for the field with the target object at the center (so-called ON-source field) showed excess events near $\alpha = 0^\circ$ compared with that for the field far from the target object (OFF-source field). The significance of the excess was more than 5 standard deviation and this became the first TeV gamma-ray object in the southern hemisphere.[26]

3.4. *Crab*

This "standard candle" is in the northern hemisphere and its elevation angle in Woomera is 53° at best. This means the energy threshold for gamma-rays becomes higher than that for the typical southern sources, since the air mass becomes larger and showers develop farther from detectors. Cherenkov light travels over far more distance but the light collection area becomes larger, thus compensating the decrease of statistics due to higher energy threshold considerably. The energy spectrum observed by CANGAROO covers the highest energy region, above 7 TeV, and the gamma-ray spectrum was shown to be extending above 50 TeV.[27,28]

3.5. *SN1006*

Discovery of non-thermal X-rays from the rim of SNR SN1006 suggested the existence of high energy electrons which may be accelerated in shock waves in SNR and.[29] Then a possible TeV emission by the inverse Compton mechanism caused by high-energy electrons responsible for synchrotron X-ray emission is predicted. The CANGAROO observations showed a gamma-ray signal from the northeast rim of this SNR.[30] The TeV spectrum is well fit by the synchrotron-inverse Compton mechanism assuming magnetic field strength of $\sim 4\mu$G and microwave background radiation photons as target photons.[31] This is a more direct evidence of high-energy electrons accelerated in SNRs, and, showed the potential of imaging atmospheric Cherenkov telescopes for ground-based gamma-ray astronomy.

3.6. *CANGAROO-II*

Successful operation of the 3.8m telescope lead the CANGAROO group to construct a totally new telescope designed exclusively for high-energy gamma-ray astronomy. The telescope drive was based on that of radio telescopes, but the reflector was newly designed. The segmented reflector of 7m in diameter consisted of 60 spherical mirrors of 80cm in diameter made of fiber-reinforced plastic with aluminized surface, which weigh about one-third of glass mirrors and reduce gravitational deformation.[32),33)] This telescope was equipped with a fine-resolution imaging camera consists of 512 photomultipliers of 1/2" diameter. The electronics and data acquisition systems were designed with state-of-art technology. This telescope was completed in March 1999.

3.7. *CANGAROO-III*

Just after the completion of the 7m telescope, we were awarded by a larger budget for construction of an array of four 10m telescopes, or CANGAROO-III.[34)] The first 10m telescope was the upgraded version of the CANGAROO telescope in March 2000 (Fig. 4). The second telescope was constructed in early 2002 with many improvements, e.g., improved plastic mirrors, a wider field-of-view camera, and faster electronics and data acquisition system. The third one was completed in late 2002 and the forth one will be finished in 2003.

Fig. 4. CANGAROO 10m telescope.

3.8. *RX J1713.7-3946*

The first result from the CAGAROO-III project was published in Nature in April, 2002.[35)] It was about an evidence of gamma-rays produced by non-electromagnetic process based on the data obtained with the first 10m telescope. The resulting spectrum was expressed by a single power law and was not compatible with spectra assuming electromagnetic processes: inverse Compton scattering or bremsstrahlung. If it is interpreted as gamma-rays derived from pion decay process, this can be the first evidence of proton acceleration in supernova remnants, which might prove the SNR origin of cosmic rays. However, taking account of the nearby EGRET unidentified source makes a fit by a simple power-law pion-derived spectrum difficult. Further stereo observation with higher angular accuracy and observations between EGRET and CANGAROO measurements may be necessary to finalize this controversial issue.

3.9. *Mrk 421*

The news of flaring activity of this first TeV blazar in February 2001 prompted the observation by the 10m telescope even at very large zenith angles which raise the detection energy threshold higher than normal observations, as in the case for the Crab nebula. The gamma-ray signal above 10 TeV[36)] is somewhat unexpected, since at the cosmological distance of $z = 0.031$ multi-TeV gamma-rays are attenuated due to the collision with cosmic infrared background radiation. The CANGAROO results may suggest that the infrared photon density could be lower than deduced from infrared satellite observations.

3.10. *NGC 253*

Another surprise was the evidence of gamma-ray emission from a normal spiral galaxy, NGC 253, but showing starburst activities.[37] The observational results indicate possible extension of the gamma-ray emission region. This suggests many interesting possibilities[38] and we need to measure the angular extent with stereo observation.

3.11. *Stereo observation*

Cherenkov light is emitted 5 to 10km above ground so that image orientations are different when observed by multiple telescopes separated by $\sim$ 100 m. Combining the images we can know the original direction of gamma-rays more accurately.[4] This improves the angular resolution to be better than 0.1° compared by the single telescope case of 0.2°. Knowing the coarse distance to showers has another merit of better energy estimation of gamma-rays. Simulation says $\Delta E/E \sim 15\%$ for stereo observation to be compared with 40% for single telescope case.[39]

The first stereo data was obtained in December 2002 with two 10m telescopes and is under analysis. The full four telescopes will be operational in 2003.

§4. Future prospects

With the completion of the CANGAROO-III telescope, we will of course revisit gamma-ray objects we have detected so far with better angular and energy resolution. At the same time we will systematically study galactic gamma-ray candidates including non-thermal SNRs as possible TeV emitters. Also other types of objects, such as blazars, pulsar nebulae, should be given observation time, which makes target selection difficult. Strategy and continuous support for long-range observation is important.

We are not alone in this field and other projects are actively going on. Ground-based projects such as MAGIC,[*] H.E.S.S.[**] and VERITAS[***] are rivals in exploration of the sub-TeV gamma-ray sky. Located in different places on earth, these telescopes can share the whole sky in the visible sky portion and different time of observation due to the rotation of the earth, which prompts the international collaboration as well as observers at other wavelength to understand the astrophysical phenomena in multiple views. At GeV energies, AGILE[†] and GLAST[††] are the satellite-based large field-of-view detectors to be launched into orbits in 2004 and

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[*] http://hegra1.mppmu.mpg.de/MAGICWeb/
[**] http://www-hfm.mpi-hd.mpg.de/HESS/HESS.html
[***] http://veritas.sao.arizona.edu/
[†] http://www.ifctr.mi.cnr.it/Agile/
[††] http://www-glast.stanford.edu/

2006, respectively. These observatories are complementary to the TeV observatories when studying high-energy objects in wider energy region and interaction with ground-based observations will be more important in the future.

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