Recent Status of CANGAROO-III

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Recent status of the CANGAROO project for high-energy gamma-ray astrophysics and recent results are reported.

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§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 by the end of 2003 for high-sensitve detection of high-energy gamma-rays in Woomera, South Australia. We have discovered new gamma-ray objects in the southern sky with unpredecented 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. Unlike radio to X-ray wavelengths, high-energy gamma-rays cannot be generated thermally and are produced only in non-thermal interactions of high-energy particles with matter and photon field.2) Thus the production site of high-energy gamma-rays is closely related to the existence, generation and acceleration of high-energy particles and to the long-standing problem of cosmic ray origin.

The earth atmosphere is not transparent for gamma-rays and satellites are the only possible gamma-ray observatories until 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 determins the practical upper limit of detectable gamma-ray energy. The EGRET detector onboard the Compton Gamma Ray Observatory lauched in 1991 has provided the most detailed knowledge of the gamma-ray sky below a few tens of GeV,3) but ground-based detection is the only way to look for high-energy phenomena in the Universe at higher energies.

§3. Imaging Cherenkov telescopes

Cosmic-ray showers are initiated by nuclear interaction of cosmic-ray protons or nuclei with atmospheric nuclei. The nuclear interaction produces many pions. Neutral pions decay promptly into two gamma-rays and develop electromagnetic showers. Charged pions interact with atmospheric nuclei again and develop 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. This difference is reflected to the image of Cherenkov light emitted by charged particles in showers which run faster than light speed of light in the atmosphere. The idea of the imaging Cherenkov telescope was proposed in late 1970's.4) Later, Hillas5) developed a method to discriminate gamma-ray showers from cosmic-ray showers using this difference of Cherenkov light image quantatively: he defined characteristic parameters called length, width, distance, concentration and showed the difference in distrtibution 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.6)

The Crab nebula was detected at high significance by the Whipple group in 19897) using this imaging technique. Then, image orientation angle toward the assumed source, or α, has been introduced as another effective image parameter.8,9) A gamma-ray signal appears as an excess events near $\alpha = 0°$ 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 1992.10)

Now there are many atmospheric Cherenkov telescopes are working in the world and watching for the gamma-ray sky at various locations, and the number of sources in the TeV gamma-ray catalog is growing year by year.11)

§4. Brief history of CANGAROO

The explosion of SN1987A prompted needs for gamma-ray observatories in the southern hemisphere. One of such projects was JANZOS, which is an acronym

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[*] See http://icrhp9.icrr.u-tokyo.ac.jp for full listings.

for Japan, New Zealand, Australia Observation of SN1987A.[12] There used three fixed 2m-diameter mirrors to detect Cherenkov light from gamma-ray showers in drift scan mode. This experiments proved the merit of having a Cherenkov telescope in the southern hemisphere, but the weather in New Zealand is not suitable for Cherenkov light and it was desired a more sensitive telescope under good night sky condition. A former lunar ranging telescope of 3.8m diameter located in Dodaira observatory of Tokyo Astronomical Observatory was found unused and could work as a Cherenkov telescope. Desert in Australia, where University of Adelaide group was operating a Cherenkov telescope called BIGRAT (BIcentinal Gamma Ray Telescope),[13] could be a good place for that telescope and this is the start of the CANGAROO project in collaboration with the University of Adelaide group.[1] 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.

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 imaging camera. The new camera, set at the prime focus of the telescope, consisted of 220 photomultiplier tubes of 3/8" diamter. 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 measument, and a VME-based single board computer was used for data aquisition with help of the online group of National Laboratory for High Energy Physics, Japan.[14]

The location of the Woomera site in the southern hemisphere is suitable for observation of galactic objects. The operation of the 3.8m telescope for 7 years yielded several discoveries of new TeV gamma-ray objects: they include the pulsar PSR 1706-44,[15] highest-energy end of the Crab nebula spectrum,[16,17] the supernova remnant SN1006,[18] the Vela pulsar,[19] and the supernova remnant RX J1713.7-3946.[20]

§5. CANGAROO-II

After the successful operation of the 3.8m telescope, which was later called CANGAROO-I, a new budget to construct a whole new telescope was approved in 1995.[21] This telescope, CANGAROO-II, was equipped with a reflector[22] consisting of sixty spherical mirrors of 80cm in diameter, which is approximately 7m aperture, with a focal length of 8m. The base material of the mirror is CFRP (carbon-fiber reinforced plastic), which was newly developed for use in Cherenkov telescopes, and makes the reflector light and reduces gravitational deformation of the parabola shape. The altitude of each mirror is remotely adjusted by stepping motors. The 7m telescope began operation in March 1999. In 1999 we obtained a new budget to construct an array of four 10m telescopes, which is now called CANGAROO-III.[23] As the first step of CANGAROO-III, the 7m telescope was expanded to 10m by addition of 54 mirrors in March 2000. Most of the results by CANGAROO-II come from this 10m telescope (Fig.1). The image of a star was measured with a CCD camera and was found to be 0.20° (FWHM). The mount of the telescope is alt-azimuth type and is based on a design of radio antennas. It can be controlled by issuing a position command by a serial line interface. The tracking accuracy was measured by observing stars with a CCD camera and was better than 1 arcminute, limited by the measurement device.

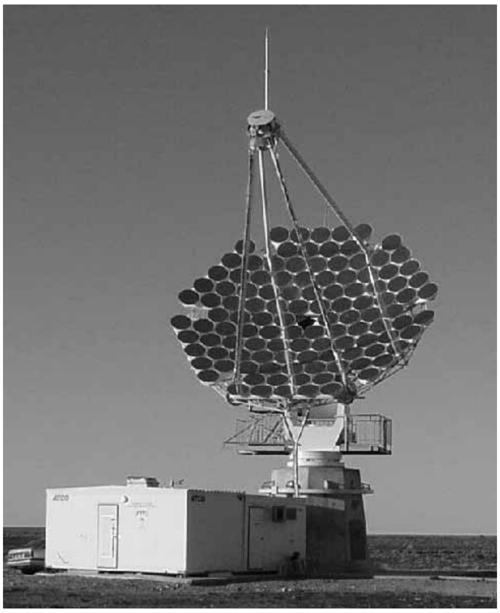

Fig. 1. The CANGAROO-II 10m atmospheric Cherenkov telescope in Woomera, South Australia.

At the prime focus we set an imaging camera consisting of 552 photomultiplier tubes (PMTs) of half-inch diameter with light-collecting cones to reduce dead space between photosensitive area of PMTs. It cover 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 frontend 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 night sky background. These event data are collected by a CPU (running Linux) and stored in a hard disk with house-keeping data such as coordinates of the telescope measured by encoders of the telescope drive, cloud monitor data which detects far infrared light to monitor sky condition, and so on.

§6. Recent results from CANGAROO-II

6.1 *Supernova remnant RX J1713.7-3946*

The first result from the CANGAROO-III project was published in Nature in April, 2002.[24] It was about an evidence of gamma-rays produced by non-electromagnetic process in a supernova remnant (SNR) 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 (Fig.2). Further stereo observation with higher angular accuracy and observations between EGRET and CANGAROO measurements may be necessary to finalize this controversial issue.

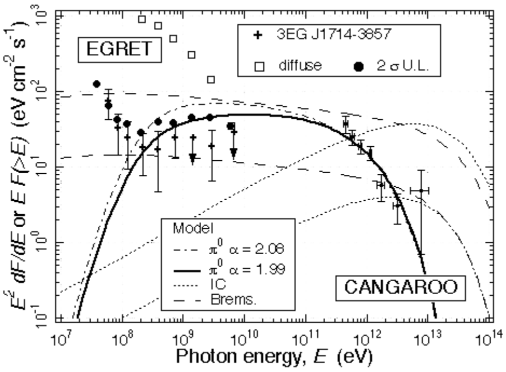

Fig. 2. The energy spectrum of RX J1713.7-3946 observed by CANGAROO. Upper limits derived from EGRET archival data and the spectrum for a nearby source, 3EG J1714-3857, is also shown. Model calculations are also shown by dot-dashed (π^0 decay from $E^{-2.09}$ proton spectrum), solid (π^0 decay from $E^{-1.99}$ proton spectrum), dotted (inverse Compton) and dashed (bremsstrahlung) lines.

6.2 *Blazar Mrk 421*

The news of flaring activity of this first TeV blazar$^{10)}$ 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 observation in Woomera. The gamma-ray signal above 10 TeV$^{25)}$ is somewhat unexpected (Fig.3), 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.

6.3 *Galaxy NGC 253*

Another surprise was the evidence of gamma-ray emission from a normal spiral galaxy, NGC 253, but showing starburst activities$^{26,28)}$ (Fig.4). The observational results indicate possible extention of the gamma-ray emission region. This suggests many interesting possibilities$^{27)}$ and we need to measure the angular extent with stereo observation.

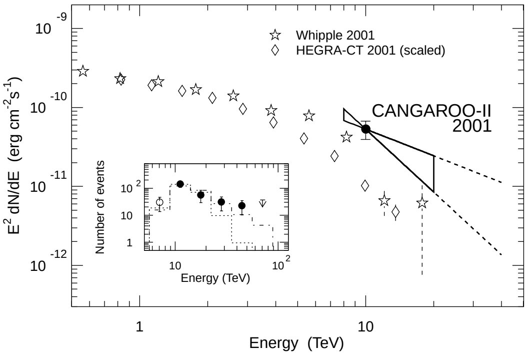

Fig. 3. The gamma-ray fluxes (main panel) and the energy spectrum of gamma ray events (inserted panel) observed by CANGAROO. In the inserted panel, data are represented by circles with error bars, with a 2σ upper limit plotted at the highest energy. Best-fit spectra for a power-law ($E^{-4.0}$; dot-dashed line) and a cut-off ($E^{-1.9}\exp(-E/4\mathrm{TeV})$; dotted line) are shown. The data shown with the filled circles were used for the spectral shape fitting. In the main panel, the measured flux under the assumption of a power-law spectrum is shown with error bars and the area corresponding to statistical errors of $\pm 1\sigma$. Whipple (Krennrich et al. 2001) and HEGRA-CT (Aharonian et al. 2002) spectra measured in similar periods are also shown. The fluxes plotted for the HEGRA-CT group have been scaled in order to normalize it to the Whipple flux at 1 TeV.

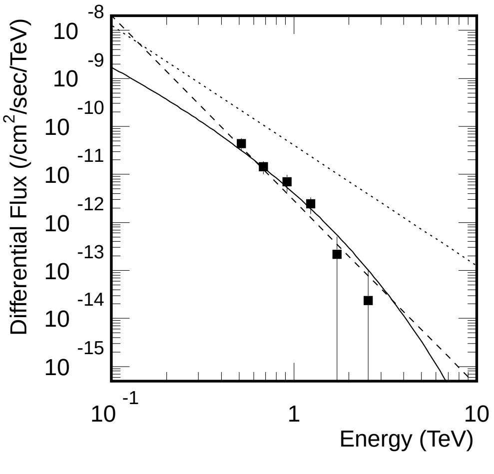

Fig. 4. The energy spectrum of NGC253 observed by CANGAROO. The dotted line is that of Crab nebula observations. The other lines are the fitting results. The dashed line is that of a power-law ($\propto E^{-3.85\pm0.46}$). The solid curve is that with an exponential cutoff ($\propto E^{-1.5}\exp(-\sqrt{E})$).

§7. CANGAROO-III

Cherenkov light is emitted 5 to 10 km 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.?) 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.29)

The second 10m telescope has been constructed in March 2002. We refined the production process of mirrors to obtain better optical quality,30) developed a new camera having wider field-of-view of about 4 degrees,31) installed faster electronics and data acquisition system,32) and developed a pattern trigger system.33) The first stereo data was obtained in December 2002 with two 10m telescopes and is under analysis. The third and fourth telescope have been completed and about to start operation. The full array of four telescopes will be operational by the end of 2003.

§8. Summary

With the completion of the CANGAROO-III array of telescopes, 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 in order to attack the long-standing problem of cosmic ray origin. 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.

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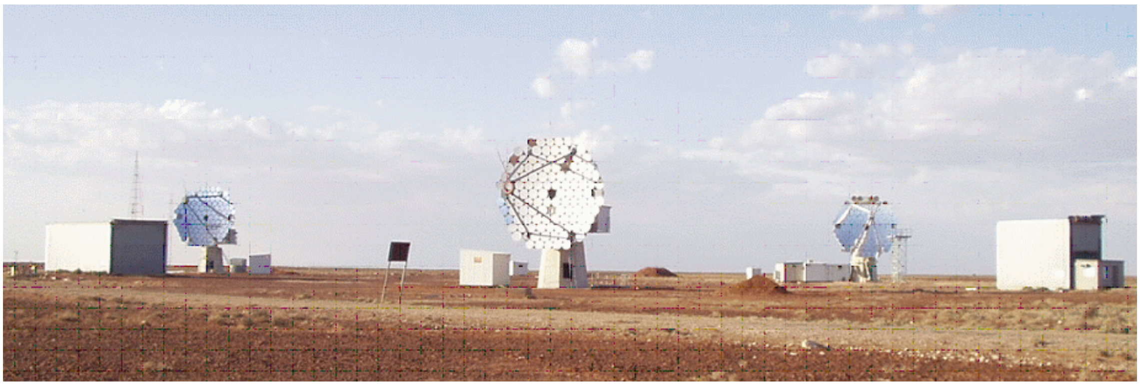

Fig. 5. Woomera site in December 2002.