TeV Gamma Ray Emission from Southern Sky Objects and CANGAROO Project

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Abstract. We report recent results of the CANGAROO Collaboration on very high energy gamma ray emission from pulsars, their nebulae, SNR and AGN in the southern sky. Observations are made in South Australia using the imaging technique of detecting atmospheric Cherenkov light from gamma rays higher than about 1 TeV. The detected gamma rays are most likely produced by the inverse Compton process by electrons which also radiate synchrotron X-rays. Together with information from longer wavelengths, our results can be used to infer the strength of magnetic field in the emission region of gamma rays as well as the energy of the progenitor electrons. A description of the CANGAROO project is also given, as well as details of the new telescope of 7 m diameter which is scheduled to be in operation within two years.
INTRODUCTION

A firm foundation for VHE (Very High Energy) gamma ray astronomy [1] was laid with the use of the imaging Čerenkov technique to detect a signal from the Crab by the whipple group [2]. Detection of VHE emission from PSR B1706−44 soon followed by the 3.8 m imaging Čerenkov telescope of the cangaroo (Collaboration of Australia and Nippon(Japan) for a GAmm Ray Observatory in the Outback) Project, which commenced operation in 1992. Gamma rays from this pulsar had been discovered by cgro egret soon after its launch. The 3.8 m telescope, located in the southern hemisphere, has the advantage of being able to study many Galactic objects near the Galactic center, while a number of Čerenkov imaging telescopes that have commenced operation in the northern hemisphere concentrate mainly on observing the Crab nebula and nearby AGNs.

THE CANGAROO PROJECT

The 3.8 m diameter telescope [3] is located near Woomera, South Australia (at 136°E and 31°S, 160 m above sea level). The camera consists of 256 photomultiplier tubes with a total field of view of about 3° diameter, enabling a fine angular resolution to construct images of Čerenkov photons. The threshold energy of detectable gamma rays from the zenith was estimated to be 1–2 TeV before November 1996. The recoating of the mirror of the telescope with aluminium has since reduced the threshold energy by a factor of 2.

Another telescope of 10 m diameter is scheduled to commence operation in 1998, to exploit the region of \( \sim 100 \) GeV energies. A radio antenna design is used for the construction of the main body of the telescope, which has an alt-azimuth mount. The light collecting mirrors attached to the parabolic antenna are spherical with 80 cm diameter and made of carbon reinforced plastic material which has the merit of having less weight than glass. We will start with a total area equivalent to a 7 m diameter mirror. The focal length is 8 m, and a camera consists of 512 photomultiplier tubes of Hamamatsu R4124 of 1 ns rise time. The diameter of the tube is 13 mm with the use of light guide to collect photons across 0.12° per tube.

RESULTS OF CANGAROO OBSERVATION

Galactic Objects

The galactic objects CANGAROO has observed are listed in Table 1. In addition to the Crab nebula [4], positive evidence has been obtained on PSR B1706-44 [5] and the Vela pulsar nebula [6].
**TABLE 1.** List of Galactic Objects of CANGAROO Observation

| objects          | integral flux (10^{-12} cm^{-2} s^{-1}) | threshold (TeV) | observation time (hrs) | references |
|------------------|-----------------------------------------|-----------------|------------------------|------------|
| Crab             | 0.8                                     | 7               | 61                     | [4], [7]   |
| PSR B1706−44     | 8                                       | ∼1              | 84                     | [5]        |
| Vela             | 2.9 (nebula)                            | 2.5             | 119 + (28)\(^{(a)}\)  | [6]        |
|                 | <1.4 (pulsar position)                  | 2.5             | 119 + (28)\(^{(a)}\)  | [6]        |
| PSR B1055−52     | <0.95                                   | 2               | 69                     | [8]        |
| PSR B1758−23     | < 2                                     | ∼1              | 48                     | [9]        |
| PSR B1259−63     | ∼ 4 ?                                   | ∼3              | 38 + (>51)\(^{(a)}\)  | [10]       |
| PSR B1509−58     | < 2                                     | 2               | 50 + (>31)\(^{(a)}\)  | [10]       |
| SN 1006          | a hint of a signal                      | ∼2              | 35 + (>30)\(^{(a)}\)  |            |

\(^{(a)}\) data taken in 1997 with analysis yet to be done

**Crab:** The Crab is seen at zenith angles of 53°−60° near its culmination from the observation site in Australia. The low elevation causes an increase of threshold energy but with an increase of detection area [4], enabling us to enjoy excellent sensitivity at ∼10 TeV energies. The energy spectrum observed extends to as high as ∼50 TeV without an apparent change of slope from the power law spectrum in 300 GeV to ∼1 TeV region [7].

**EGRET pulsars; PSR B1706−44 and Vela pulsar:** These two EGRET pulsars are found to be VHE gamma ray emitters, but there is no evidence of VHE emission from PSR B1055−52 [8]. The signals from PSR B1706−44 [5] and the Vela [6] show no modulation with the pulsar spin period, which suggests that pulsar nebula is, like the Crab, responsible for the VHE emission. The ratio of the observed VHE to X-ray luminosity of the nebulae are larger than in the case of the Crab. The regime of synchrotron and inverse Compton processes of relativistic electrons to radiate X and gamma rays then indicates that the magnetic field in the nebulae is about two orders of magnitude weaker than the Crab nebula. VHE gamma rays are spatially peaked as offset to the south-east direction from the Vela pulsar by about 0.13°, and the spatial size of emission appears broader than the point spread function. The contribution from the pulsar position is given as the upper limit from the pulsar position in Table 1. We expect that our 1997 data with a reduced gamma ray threshold energy will be useful to infer the VHE spectrum. More knowledge with better accuracy, particularly on the energy spectrum both in X-ray and VHE bands, are required to restrict parameters of emission models and to infer the structure of the nebulae.

**Other sources:** Observations have not been made yet for objects such as young, short period pulsars or X-ray binaries, which are not detected by EGRET so far but on which extensive VHE efforts have been made [12].

Among the binary pulsars, PSR B1259−63 is a peculiar object that has a highly eccentric orbital motion around a giant companion Be star. A VHE signal of ∼4σ
was detected near the time of the previous periastron in 1994, and confirmation will be sought in the data from around the next periastron in May 1997.

Supernova remnants are another target of prime importance for VHE gamma ray study. One of the unidentified EGRET sources is coincident with the SNR W28 which is possibly associated with PSR B1757–24. Evidence for point source emission was not detected for either W28 or PSR B1758–23 [9], though we can not exclude VHE emission, as appears in the earlier data [11], from the vicinity of the center of EGRET error circle which is apparently shifted from W28 towards the giant molecular cloud M20. Searches remain necessary for the unknown position of VHE emission possibly extended in the complex system of SNR, molecular cloud and pulsar. PSR B1509–58 is also embedded in a complex structure of plerion activity, and a considerable amount of data has been accumulated. An opportunity for VHE gamma rays to show direct evidence of shock acceleration of relativistic particles at the supernova shell is provided by shell type supernovae, such as SN1006 from which the ASCA satellite detected non-thermal X-rays to suggest progenitor electrons up to $\sim 100$ TeV [14].

Active Galactic Nuclei

No TeV signal has been detected from nearby southern AGNs; Cen A; PKS 0521–36 ($z=0.055$); PKS 2316–42 ($z=0.055$); PKS 2005–49 ($z=0.071$); EXO 0423–08 ($z=0.039$) etc. [13]. The upper limits are around $\sim 1 \times 10^{-12}$ cm$^{-2}$ s$^{-1}$ at 2 TeV, which lies near the quiescent Whipple flux levels of the northern BL Lac objects which are VHE sources, i.e., Mrk 421 and 501.

DISCUSSIONS AND SUMMARY

The CANGAROO detections are summarized in Fig. 1. The vertical axis is the product $F \cdot E$ (in the unit of erg cm$^{-2}$ s$^{-1}$) of integral photon flux $F$ and threshold energy $E$, and the horizontal axis the observation time used for analysis. The detection sensitivity is near $10^{-12}$ erg cm$^{-2}$ s$^{-1}$ which corresponds to a luminosity of $10^{32}$ erg s$^{-1}$ at a distance of 1 kpc. The significance of detection limited by statistical fluctuations is shown by the dotted line (Fig. 1), which is normalized to the detection of 100 gamma rays at 1 TeV over 20 hrs. The preliminary result on PSR B1259–63 is marked by “B”. “S” indicates the flux due to the inverse Compton process expected from SN1006 when the magnetic field is as weak as the interstellar value. Loose upper limits on PSR B1509–58 and on the Vela pulsar position are given due to a limited sensitivity of the current technique of imaging Čerenkov photons to spatially extended emission.

VHE gamma rays have a unique role to provide information about the high energy nature of these objects. There are an increasing number of interesting Galactic objects; unidentified EGRET sources, pulsar nebulae and SNRs of non-
thermal X-rays, objects with relativistic jets etc., and CANGAROO will continue to enjoy a ‘hard time’ in choosing the targets for observation.

The project is supported by a Grant-in-Aid for Scientific Research of the Japan Ministry of Education, Science, Sports and Culture, and also by the Australian Research Council.

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