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Observations of extended VHE gamma-ray emission from MSH 15-52 with CANGAROO-III

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Abstract: The gamma-ray pulsar PSR B1509-58, surrounded by the supernova remnant MSH15-52, was expected to be a Very High Energy gamma-ray source. The CANGAROO-I 3.8 m telescope reported a marginal detection of VHE gamma-rays above 1.9 TeV and recently H.E.S.S. detected an extended signal along with the pulsar jets, from sub-TeV to tens of TeV. We observed MSH15-52 using CANGAROO-III imaging atmospheric Cherenkov telescope array located in South Australia, from April to June in 2006. We observed gamma-rays above 810 GeV with 7 σ level during a total exposure of 48.4 hours, which is consistent with that of H.E.S.S.. Its morphology shows an extended emission compared to our Point Spread Function. We discuss the possible origin of the high energy emission by multi wavelength spectral analysis and energetics.

Introduction

PSR B1509-58 was detected in the radio supernova remnant MSH15-52(G320.4-1.2) initially as a 150-ms X-ray pulsar by *Einstein* satellite[1]. Subsequently its pulsation was observed at radio frequencies[2], and soft γ-rays by COMPTEL[3]. However EGRET did not detect the clear pulsation at the hard γ-ray band[3]. One of the most energetic young pulsar PSR B1509-58 has the highest period derivative $\dot{P} = 1.5 \times 10^{-12}$, the characteristic age $\tau = 1700$ yr, the relatively high spin-down luminosity $\dot{E} = 1.8 \times 10^{37}$ erg/s [4]. The radio morphology of MSH15-52 consists of the southeast and northwest shells. The latter spatially coincided with the H II region, RCW89. MSH 15-52,PSR B1509-58 and RCW89 were concluded to be associated systems and the distance to be 5.2 ± 1.4 kpc[5]. Outflow jets, similar to the Crab or the Vela pulsar, were observed by *ASCA* [6], *ROSAT*[7] or *Chandra*[8] and the one towards northwest was terminated at RCW89. *BeppoSAX* detected nonthermal emission from 1 keV up to 200 keV with $\Gamma = 2.08 \pm 0.01$ [9], while the recent observations of *INTEGRAL* satellite found a possible spectral cut off at ~ 160 keV[10]. Since high energy electrons existed, very high energy γ-ray emission was predicted via inverse Compton(IC) scattering with cosmic microwave background(CMB) photons[11]. CANGAROO-I also suggested a possible VHE γ-ray detection of $\sim 10\%$ Crab flux above 1.9 TeV, assuming the spectral index of 2.5[12]. After that H.E.S.S. reported an extended VHE γ-ray emission along with the pulsar jet. Their TeV morphology showed a good coincidence with the X-ray images, indicating that TeV γ-rays originated with the inverse Compton scattering of relativistic electrons. On the other hand it was pointed out that IC radiation with CMB did not dominantly account for TeV flux, which indicated contributions of IR photons as seed photons on the IC process[13, 14]. Here we report the result of CANGAROO-III observations.

Observation and Result

CANGAROO-III is an array of four imaging atmospheric Cherenkov telescopes (IACTs), located at Woomera, South Australia (136°47′E, 31°06′S, 160m a.s.l.). Each telescope has a 10m-diameter reflector which consists of 114 segmented FRP spherical mirrors[15] mounted on a parabolic frame. The telescopes are placed at the corner of a diamond shape with an interval of ~ 100 m[16]. The oldest telescope T1, which was the CANGAROO-II, is not used due to its smaller FOV and higher energy threshold. Imaging camera systems on the used three telescopes (T2, T3 and T4) are identical and their FOV are 4.0° with 427 PMTs for each, given in Kabuki et al.(2003) in detail.

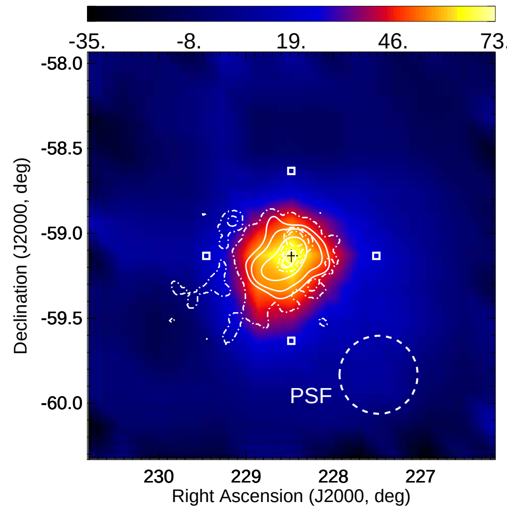

Figure 1: Morphology of TeV emission. Positions of the pulsar and tracking are indicated by a cross and squares. Our PSF is also shown. Solid contour and dot-line contours represent H.E.S.S. and ROSAT results, respectively.

The observations were made from April to June in 2006. The tracking positions were offset by $\pm 0.5°$ from PSR B1509-58 in declination or in right ascension and changed every twenty minutes for the purpose of suppressing local effects on the camera plane by 4.1 and 4.5 magnitude bright stars. We rejected data taken in bad weather conditions from analysis and finally the selected data were taken at a mean zenith angle of $30.1°$ and a typical trigger rate of 3-fold coincidence was 12 Hz. A total live time was 48.4 hours. The analysis procedures were described in the reference[17] and [18].

We detected 427 $\pm$ 63 excess events with a point source assumption ($\theta^2 < 0.06$) and also 582 ± 77 events within $\theta^2 < 0.1$ above 810 GeV. The TeV emission is extended, and a smoothed morphology of γ-ray like events is shown in Fig.1. Numbers of events were individually estimated by the FD-fitting method in each sky bin of a $0.2° \times 0.2°$ square. Intrinsic standard deviations of TeV emission were estimated by the 2D Gaussian fit convolved by our PSF on our unsmoothed excess map. The inclination of the major axis was $29.8 \pm 1.9°$ from north to west and the deviations along the major and minor axes were calculated to be $0.07 \pm$

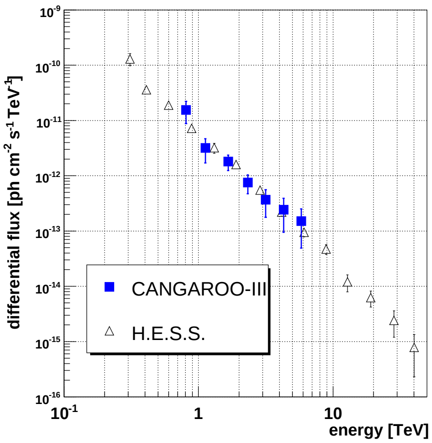

Figure 2: Differential TeV flux obtained by CANGAROO-III(filled squares), compared with those of H.E.S.S.(open triangles).

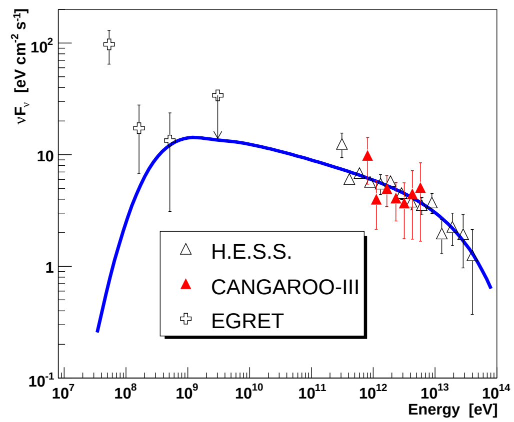

Figure 3: Spectral energy distribution and a pion decay model curve(solid line).

$0.07°$ and $0.21 \pm 0.08°$, respectively. Fig. 2 represents a reconstructed VHE γ-ray spectrum compatible with a single power-law and a typical value is at 2.35 TeV $(6.8 \pm 1.6_{\rm stat} \pm 2.9_{\rm sys}) \times 10^{-13}$ cm^{-2}s^{-1}TeV^{-1} with a photon index of $2.31 \pm 0.51_{\rm stat} \pm 0.36_{\rm sys}$. Our result shows the stability of the TeV emission between H.E.S.S. observation in 2004 and ours in 2006.

Discussion

We discuss the possible origin of the TeV emission from the pulsar wind nebula. Here the constraint on the total energy of accelerated particles is estimated 10^{48} ergs, which is obtained by the integration of the pulsar's spin down luminosity during the characteristic age of the pulsar 1700 yr with a simple assumption of a constant spin-down $\dot{P} = 1.5 \times 10^{-12}$. First we examined a pion decay model as a TeV origin. Fig. 3 shows a spectral energy density(SED). We assumed the population of accelerated protons to be expressed by a single power-law with an exponential cutoff. Only ours and H.E.S.S.[13] data were used for the fit since EGRET data were the sum of pulsed and unpulsed emission[3] which may contain the emission from the pulsar. The best fit curve is shown in Fig. 3 by the solid line. The power-law index and the cutoff

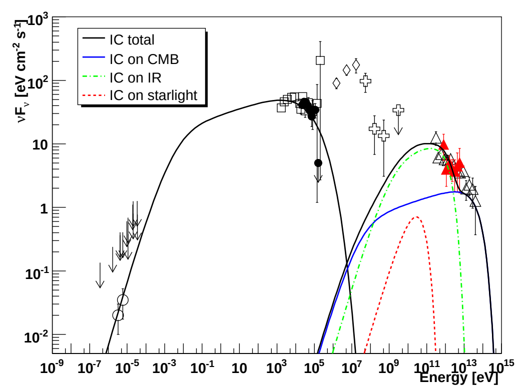

Figure 4: SED and a preliminary leptonic model curve.

energy were obtained as 2.16 ± 0.05 and 530 ± 399 TeV, respectively. Assuming the interstellar matter density simply as 1 cm^{-3}, the total energy of high energy protons above 1 GeV was calculated to be 3.2×10^{51}ergs. The spin-down energy could not drive the acceleration of protons during its characteristic age, even if the known ambiguity of the distance was taken into account.

Second we discuss the leptonic scenario, and here we used a simple one-zone IC model to reproduce the multi-wavelength spectra. The multi band SEDs are plotted on Fig. 4. The data points derived from this work were represented by red closed triangles, H.E.S.S. by open triangles[13], EGRET by open crosses, COMPTEL by open diamonds[3], *INTEGRAL* by closed circles[10], *BeppoSAX* by open circles[9] and ATCA by open circles[8]. Arrows in the radio band show whole emission from MSH 15-52 or RCW89 listed in [11], and then we treated them as upper limits on the faint PWN. COMPTEL and EGRET fluxes, containing pulsed emission[3], can be also considered to be upper limits to the nebular unpulsed emission. We found some difficulties in reproducing these spectra. The first one was the lack of the amount of target photons as discussed in [13]. CMB field density couldn't account for TeV flux, and hence we added IR and optical(starlight) photon field as well as [13]. Here we used 100 μm black body radiation from interstellar dusts and 6000 K radiation from stars. The second one was the possible cutoff about 160 keV of *INTEGRAL* result. This limit was too strict to drop synchrotron spectrum steeply. However it was a 1σ upper limit[10] and also within the *BeppoSAX*/PDS errors, and then we allowed the model curve to exceed this limit. The reproduced curve is shown in Fig. 4 with an assumption of a broken power-law electron spectrum. Here the uniform magnetic field $B = 17\mu$G and IR field density $U_{IR} = 2.5$ eV/cc were used. By integrating an electron energy above 1 GeV the total energy amounts up to 7×10^{48} ergs, which exceeded the limitation.

Conclusion

CANGAROO-III observed PSR B1509-58 in the SNR MSH15-52 for 48.4 hours in 2006 and detected VHE γ-ray signals at 7σ level. The obtained differential flux and the intrinsic extension of TeV emission were consistent with previous H.E.S.S. result. The study of the multi-wavelength spectra based on PWN origin showed the hadronic scenario was rejected due to the energetics. In the leptonic scenario, from the point of view of the energetics it is preferred a single power law electron model or a softer index especially at the lower energy part of electrons in order to reduce the amount of the total energy.

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