CANGAROO-III SEARCH FOR GAMMA RAYS FROM SN 1987A AND THE SURROUNDING FIELD

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ABSTRACT

Optical images of SN 1987A show a triple-ring structure. The inner (dust) ring has recently increased in brightness and in the number of hot spots, suggesting that the supernova shock wave has collided with the dense preexisting circumstellar medium, a scenario supported by radio and X-ray observations. Such a shocked environment is widely expected to result in the acceleration of charged particles and the accompanying emission of very high energy gamma-rays. Here we report the results of observations made in 2004 and 2006, yielding upper limits on the TeV gamma-ray flux, which are compared with a theoretical prediction. In addition, we set upper limits on the TeV flux for four high-energy objects which are located within the same field of view of the observation: the superbubble 30 Dor C, the Crab-like pulsar PSR B0540–69, the X-ray binary LMC X-1, and the supernova remnant N157B.

Subject headings: gamma rays: observation — supernovae: individual (SN 1987A)

1. INTRODUCTION

SN1987A was the closest observed supernova in 380 years, and the evolution of the remnant of this supernova has been studied in great detail over the past 20 years. The radio intensity is growing and its rate of increase is increasing, with the spectral index being observed to flatten (Staveley-Smith et al. 2007). Imaging at radio wavelengths has made it possible to trace the expansion of the inner ring and is revealing increasing structure in the inner ring. The X-ray fluxes observed with XMM-Newton and Chandra also continue to rise almost exponentially (Habert et al. 2006; Park et al. 2007). Around ~4000 days after the supernova the X-ray light curve increased dramatically, an effect attributed to the arrival of the supernova blast wave at the equatorial ring of circumstellar material. There is some evidence that the X-ray flux is mainly thermal, indicating the blast-wave interaction with dense matter (Park et al. 2007).

Berezhko & Ksenofontov (2006) compared radio and X-ray data with their calculations and concluded that there is a high (amplified) magnetic field inside the supernova remnant. The predicted TeV gamma-ray flux, resulting mostly from the decay of neutral pions produced in interactions of the accelerated cosmic rays, is almost 1 order of magnitude below the level obtained in previous searches by Imaging Atmospheric Cerenkov Telescopes (IACTs) such as CANGAROO-II in 2001 (Enomoto et al. 2003) and HESS in 2003 (Rowell et al. 2005). The wide field of view searched by HESS did, however, yield marginal excesses in a region northeast of SN 1987A and at LMC X-1.

CANGAROO-III is one of two stereoscopic IACTs located in the southern hemisphere. With a threefold coincidence, the sensitivity is significantly improved over the previous single telescope (CANGAROO-II). We also increased the observation period by a factor of 2 in the 2006 observations compared to the 2004 and 2001 seasons. Here we report the results of these observations.

The previous HESS analysis considered not only SN 1987A but also four other high-energy objects in the same field of view (Rowell et al. 2005). We follow that idea and present upper limits on the integral gamma-ray fluxes from the superbubble 30 Dor C, the Crab-like pulsar PSR B0540–69, the X-ray binary LMC X-1, and the supernova remnant N157B. Superbubbles are expected to be efficient accelerators of cosmic rays (Parizot et al. 2004) and a shell feature near the star 30 Dor C, within 5′ of SN 1987A, shows an indication of nonthermal hard X-ray emission (Bamba et al. 2004). The energy required to produce the bubble is estimated to be $7 \times 10^{51}$ ergs, which is higher than generally expected for a single supernova remnant (Ueno et al. 2003). The other three sources belong to categories of high-energy astrophysical objects that may accelerate particles to TeV energies, but, considering their large distance of 50 kpc, they are less likely to be detected by current IACTs than their Galactic counterparts. However, as they are well within the field of view of the CANGAROO-III telescopes, and given the marginal HESS excess toward LMC X-1, it is straightforward to search for any evidence of gamma-ray emission from them.
2. CANGAROO-III STEREOSCOPIC SYSTEM

The CANGAROO-III stereoscopic system consists of four imaging atmospheric Cerenkov telescopes located near Woomera, South Australia (S31°, E137°). Each telescope has a 10 m diameter segmented reflector consisting of 114 spherical mirrors each of 80 cm diameter (Kawachi et al. 2001), providing a total light collecting area of 57.3 m². The spherical segments are mounted on a parabolic frame with a focal length of 8 m. The first telescope, T1, which was the CANGAROO-II telescope (Enomoto et al. 2002b), was not used for these observations due to its smaller field of view and higher energy threshold. The second, third, and fourth telescopes (T2, T3, and T4) were used for the observations described here. The camera systems for T2, T3, and T4 are identical and are described in Kabuki et al. (2003). The telescopes are located at the east (T1), west (T2), south (T3), and north (T4) corners of a diamond with sides of ~100 m (Enomoto et al. 2002a).

3. OBSERVATIONS

The observations were carried out in the periods from 2004 November 11 to 14 (MJD 53,320–53,323) and from 2006 December 12 to 27 (MJD 54,081–54,096) using the “wobble mode,” in which the pointing position of each telescope was shifted in declination between ±0.5° every 20 minutes (Daum et al. 1997) from the target: (R.A., decl. [J2000.0]) = (83.866139°, –69.269577°). We took no OFF source runs. The most sensitive region of the field of view is within 1° of the average pointing position. LMC X-1 is located 0.6° southeast from SN 1987A. Considering our angular resolution of 0.24°, there is some overlap between SN 1987A, 30 Dor C, PSR B0540–69, and N157B.

In the 2004 observation, data with GPS time stamps were recorded for T2, T3, and T4 individually when more than four photomultiplier (PMT) signals exceeded 7.6 photoelectrons (P.E.) threshold. The trigger and control backgrounds are generated from Monte Carlo simulations which we previously used in Vela pulsar analysis (Enomoto et al. 2006a) to separate “sharp” (gamma-ray–like) images from “smeared” (background) ones. The values of $\mu_{BG}$, $E_{BG}$, $\sigma_{BG}$, and $E_{SIG}$ can be calculated from the Monte Carlo and observational data (OFF-source runs), respectively.

In order to derive the gamma-ray likeliness, we used the Fisher discriminant (FD; Fisher 1936; Enomoto et al. 2006a). Input parameters were

$$P = (W2, W3, W4, L2, L3, L4),$$

where $W2$, $W3$, $W4$, $L2$, $L3$, and $L4$ are energy-corrected widths and lengths for the T2, T3, and T4, and assume that a linear combination of

$$FD = \alpha \cdot P,$$

provides the best separation between signal and background, then the set of linear coefficients ($\alpha$) should be uniquely determined as

$$\alpha = \frac{\mu_{SIG} - \mu_{BG}}{E_{SIG} + E_{BG}},$$

where $\mu$ is a vector of the mean value of P for each sample and E is their correlation matrix. We previously used it in Vela pulsar analysis (Enomoto et al. 2006a) to separate “sharp” (gamma-ray–like) images from “smeared” (background) ones. The values of $\mu_{SIG}$, $\mu_{BG}$, $E_{SIG}$, and $E_{BG}$ can be calculated from the Monte Carlo and observational data (OFF-source runs), respectively.

We rejected events with any hits in the outermost layer of a camera (“edge cut”). These rejected events suffer from finite deformations, especially in the length distribution, which results in deformations of the FD.

We then derived FD distributions position by position. Comparing those in the signal region and control background region, we can determine the gamma-ray–like events. Here we use Monte Carlo simulations to determine the FD distribution of gamma-ray signals. Note that in the gamma-ray simulations we used a spectrum proportional to $E^{−2.7}$. The fit of the FD distribution of source position with the above emulated signal and control background functions were carried out to derive the number of gamma-ray–like events. This is a one-parameter fitting with the constraint that sum of signal and background events corresponds to the total number of events. These coefficients can be derived exactly analytically.

5. RESULTS

The threshold of this analysis is considered to be ~1 TeV, which is higher than the typical CANGAROO-III threshold due to the larger zenith angle of the observations, of around 40°. In order to derive morphology, we segmented the field of view into $0.2 \times 0.2$ deg² square bins. The FD distributions for corresponding bins are made and fitted. The control-background region is defined as the second closest layer, which is more than 0.3° from the center of target region, i.e., larger than the 0.24° point-spread function (PSF). The statistics of the control background is, therefore, 16 times larger than that of signal bin. The results are shown in Figure 1.

The left panel is obtained from the 2004 data and the right from 2006. The average telescope pointing position is indicated by the cross centered and labeled as “SN 1987A.” with the other four high-energy objects within this field of view indicated by crosses. Our sensitivity is considered to be limited up to 1° in radius from the center. The PSF is considered to be a 0.24° radius circle. The significance distributions (excess divided by the statistical error) are approximately normal (Gaussian) distributions. The best-fit Gaussians have mean values of $−0.31 \pm 0.08$ (2004)
and $-0.18 \pm 0.09$ (2004) and standard deviations of $1.21 \pm 0.06$ (2004) and $1.31 \pm 0.06$ (2006), within systematic uncertainties.

At first we investigate the region of SN 1987A. Note that this region at some energies is contaminated by 30 Dor C, a highly energetic source. To indicate the excess distribution from its center, we show so-called $\theta^2$ distributions in Figure 2.

Here the control-background sample was selected in the region $\theta^2 = 0.1-0.2$ (deg)$^2$. The background-subtracted signals are shown. Both 2004 and 2006 data have statistically insignificant excess near $\theta^2 = 0$. The $\chi^2$/dof (degrees of freedom) for null assumptions are 18.6/15 and 13.2/15 for 2004 and 2006, respectively. These statistically insignificant excesses appear as the small excess count peaks around the centers of the plots in Figure 1. Note that our PSF corresponds to $\theta^2 < 0.06$ deg$^2$. We therefore proceed assuming that there is no signal present. In order to show the consistency between 2004 and 2006, the vertical unit is unified to count rate.

In order to determine whether or not there is a gamma-ray excess around SN 1987A, we made the FD distributions within the PSF. The control-background was made from the region $\theta^2 = (0.1-0.2)$. The fitting results are shown in Figure 3.

The background level differs between the two years. This is due to sky conditions, mirror reflectivity, time-dependence of the

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**Fig. 1.** — Excess count maps. The left panel is obtained from the 2004 data, and the right from the 2006 data. The average pointing center is SN 1987A itself. The positions of four other high-energy objects are also indicated (black crosses with labels). The PSF is shown by the black dashed circle. The white contours are derived from 4.85 GHz PMN survey radio data (Wright et al. 1994) obtained from SkyView (NASA) (NASA 2007).

**Fig. 2.** — Distributions of $\theta^2$ (deg$^2$). The left panel is obtained from the 2004 data, and the right from the 2006 data. The vertical scale is normalized to counts minute$^{-1}$ bin$^{-1}$ (0.2 deg$^2$). The background-subtracted signals (obtained by the fitting procedure described in the text) are plotted.

**Fig. 3.** — FD distributions. The left panel is obtained from the 2004 data, and the right the 2006 data. The vertical scale is counts minute$^{-1}$ bin$^{-1}$ (arbitrary unit). The black crosses are obtained from the on-source region (centered around SN 1987A within the PSF), the green histograms the best fit of the control backgrounds, the blue crosses the background-subtracted signals, and the red histograms the best-fit signal distributions.
blur spot size (which improves after maintenance periods), etc. These are considered to be the major systematics for estimating the observational gamma-ray flux in this work. For the light correction efficiency, we may have 10% uncertainty at maximum.

Again there is no statistically significant excess. We carried out a similar analysis, year by year, energy threshold by energy threshold. The obtained 2σ upper limits (ULs) are listed in Table 1.

Here we used a $E^{-2.1}$ spectrum for the gamma-ray simulation. The ULs range from 6%–17% crab. The worse upper limits in the lower energy range originated from the statistically insignificant excess around the center of the field of view. At higher energies, we do not see any excess.

The four other high-energy sources in the surrounding region, 30 Dor C, PSR B0540–69, LMC X-1, and N157B, can be analyzed in the same way. They are all within a 1′ circle from the average pointing position (the sensitive region). The summary is listed in Table 2.

These are 2 yr averages. Note that, considering our PSF of 0.24′, SN 1987A and 30 Dor C are highly confused, with other pairs being less confused. Also some of the control background regions are confused. The acceptance is a slowly and smoothly decreasing function and is reduced to 65% at a distance of 1′ from the center.

6. DISCUSSION

Our morphology indicates a negligibly small excess near the center of field of view both in the 2004 and 2006 data. This is statistically <2σ each year. We note that a similar feature can also be seen in the HESS data shown in Figures 2 and 3 of Rowell et al. (2005). A deep survey, i.e., longer observation, around this region is awaited. The region around LMC X-1 is consistent with the theoretical prediction even 7300 days after the supernova. The lines are obtained from Fig. 4 of Berezhko & Ksenofontov (2006). The solid and dashed curves are the predictions of the gamma-ray flux 8249 and 7300 days after the supernova, respectively.

Note.—The 2004 and 2006 data were averaged.

| Target      | Excess Upper Limit Events | Flux Upper Limit (cm$^{-2} s^{-1}$) |
|-------------|---------------------------|-----------------------------------|
| SN 1987A    | 126                       | $1.8 \times 10^{-12}$             |
| 30 Dor C    | 165                       | $2.5 \times 10^{-12}$             |
| PSR B0540–69| 66                        | $1.1 \times 10^{-12}$             |
| LMC X-1     | 74                        | $1.1 \times 10^{-12}$             |
| N157B       | 167                       | $2.4 \times 10^{-12}$             |

Note.—See http://www.mpi-hd.mpg.de/htm/CTA.
For the other three high-energy objects, we set upper limits far below those of previous observations. We, however, could not find any physically important constraints on their activity at high energies, again due to the distance of 50 kpc.

7. CONCLUSION

We have observed SN 1987A at two epochs: MJD 53,320–53,323 (2004 November) and MJD 54,081–54,096 (2006 December), approximately 6500 and 7200 days after the supernova, respectively. The effective observation times are 10.5 and 20 hr, respectively. No statistically significant gamma-ray signals were obtained, and we set 2σ upper limits on the integral fluxes of 6%–17% crab at ∼1 TeV. These are slightly lower than the previous CANGAROO-II and HESS upper limits. Although theory predicts a factor of ≥3 lower flux 7300 days after supernova, it also predicts that the future flux level might exceed the sensitivity limit of the existing and future arrays. Continued monitoring of this object at TeV energies therefore remains meaningful to constrain theoretical models. It is also important to improve the sensitivity of the observation methods, as proposed by the CTA project.

In addition, we set 2σ upper limits for four more high-energy objects inside our field of view: 30 Dor C (supernova), PSR B0540–69 (Crab-like pulsar), LMC X-1 (X-ray binary), and N157B (supernova remnant).

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