

# Search for TeV gamma-rays from SN 1987A in 2001

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## ABSTRACT

We searched for TeV gamma-rays from the remnant of SN 1987A around 5400 days after the supernova. The observations were carried out in 2001, from November 16 to December 11, using the CANGAROO-II Imaging Atmospheric Cherenkov Telescope. In total, 708 minutes of ON- and 1019 minutes of OFF-source data were obtained under good conditions. The detection threshold was estimated to be 1 TeV, due to the mean zenith angle of 39°. The upper limits for the gamma-ray flux were obtained and compared with the previous observations and theoretical models. The observations indicate that the gamma-ray luminosity is lower than  $1 \times 10^{37}$  erg s<sup>-1</sup> at  $\sim 10$  TeV.

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## 1. Introduction

The explosion of SN 1987A on February 23, 1987, in the Large Magellanic Cloud, was first detected as a short neutrino burst (Koshiba et al. 1987; Hirata et al. 1987; Bionta et al. 1987). It was subsequently detected at almost all wavelengths of the electromagnetic spectrum (see, e.g., Chevalier (1992), McCray (1993) and references therein). After a weakening of the emission, in accordance with the standard lightcurve for a core collapse supernovae of Type II, at present it shows a con-

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tinuous increasing brightness in radio (Manchester et al. 2002) and X-ray bands (Park et al. 2002).

Although observational efforts in the high-energy gamma-ray region were intensively carried out for several years (Raubenheimer et al. 1988; Ciampa et al. 1988; Bond et al. 1988a,b, 1989; Allen et al. 1993a,b; van Stekelenborg et al. 1993; Yoshii et al. 1996), no positive signals were obtained, with the possible exception of a 2-day TeV gamma-ray burst (Bond et al. 1988b). No observations since 1991 have been reported, despite the fact that models predict an increasing flux of high energy gamma-rays as the SN shock wave expands.

It is now 15 years since SN 1987A. Even an upper limit for the current period of the supernova remnant evolution would be very important to constrain models for gamma-ray emission. The technology used to detect very high-energy gamma-rays has improved significantly over this 15 year period, particularly with the development of Imaging Atmospheric Cherenkov Telescopes (IACTs). IACTs detect optical Cherenkov photons produced by electrons in cascades initiated by the interaction of gamma-rays at sub-TeV energies in the Earth's upper atmosphere. The Cherenkov photons are strongly beamed in the direction of the incident gamma-ray. The CANGAROO-II telescope was, at the time of these observations, the only one located in the southern hemisphere.

The CANGAROO-II telescope is located near Woomera, South Australia. Technical details are presented elsewhere (Tanimori et al. 2003), and its performance is described in Enomoto et al. (2002b); Okumura et al. (2002); Itoh et al. (2002). The 10 m diameter telescope has an effective area of 57 m<sup>2</sup>. SN 1987A can be seen at a zenith angle of 38° at its culmination. As a result, we can measure the TeV region with a significantly better sensitivity than in previous measurements. We report here on the results of observations of SN 1987A.

## 2. Observations and Analysis

The observations were carried out in 2001 over ten moonless nights between November 16 and to December 11. In total, 1275 min. of ON- and 1301 min. of OFF-source data were recorded. We removed the cloudy periods from the data and se-

lected 708 min. of ON- and 1019 min. of OFF-source data. The procedures and further details of the analysis can be found in Itoh et al. (2003).

Briefly, in the analysis, “cleaning” cuts were applied to the pixelized-camera images (each pixel being 0.115° square), requiring that each pixel have greater than  $\sim 3.3$  photoelectrons, that the Cherenkov photons arrived within  $\pm 40$  nsec, and that a cluster of at least five adjacent triggered pixels was contained in each event. After these pre-selections, we carried out a shower image analysis using the standard set of image parameters, *distance*, *length*, *width*, and  $\alpha$  (Hillas 1985), combining the *length* and *width* (after an initial *distance* cut) to assign the likelihoods to each event (Enomoto et al. 2002a). The likelihoods for both a gamma-ray origin and a cosmic-ray proton origin were calculated. The cut that was used to reject background events was based on the ratio of these two likelihoods. After these cuts, the image orientation angles ( $\alpha$ ) were plotted. A gamma-ray signal would appear as an excess at low  $\alpha$  after the normalized OFF-source  $\alpha$  distribution is subtracted from the ON-source distribution. As shown in Figs. 1 a)–f), no statistically significant excess of events with  $\alpha < 15^\circ$  was observed. From top (a) to bottom (f) in Fig. 1, six different thresholds, which are shown in Table 1, were applied to the analysis. Our Monte Carlo simulations predicted that 73% of the events from a point source would have  $\alpha < 15^\circ$  at these zenith angles.

## 3. Upper limits on the gamma-ray flux

The upper limits to the emission at each energy was obtained by adding the statistical and systematic errors to any excess events in the relevant plot in Fig. 1. The total error was the square root of the quadratic sum of both errors. These errors were doubled to obtain  $2\sigma$  Upper Limits (ULs). In the case of a negative excess, only the errors were used to determine the upper limit.

The derivation of the integral flux depends on the unknown energy spectrum of the incident gamma-rays. We therefore tried several power-law energy spectra ( $E^{-\gamma}$ ) in Monte Carlo simulations in order to determine the corresponding effective area of the observations. Three spectra, with differential flux power-law indices of  $\gamma = 2.0, 2.5,$  and  $3.0,$  were tested. In all cases, the energy ranges of

the generated gamma-rays were 0.15–20 TeV. We obtained integral flux upper limits under various assumptions, as shown in Table 1. Although the threshold energies varied as expected with initial power-law indices, the spectral responses roughly agreed with each other. We therefore adopted  $\gamma = 2.0$ , plotted in Fig. 2 by the dotted line with arrows, together with the previous measurements and model predictions.

#### 4. Discussion

In Fig. 2 we compile the upper limits on the flux of gamma rays from SN 1987A of this observation (dotted line with arrows) and those reported by others at different times since the explosion. Theoretical predictions by Berezhko and Ksenofontov (2000) (solid line), which correspond to a time of  $\sim 5000$  days, and by Gaisser, Harding and Stanev (1989) (dashed line), which is almost constant in time, are also shown.

The upper limits of this observation are significantly better than those of previous observations. In particular, at 3 TeV it is a factor of 20 lower than that of Bond et al. (1988b). At 1 TeV, the upper limit is tightened by a factor of 3, and at the highest point (several TeV) it is improved by a factor of 50. Previous measurements calculated typical luminosity upper limits of several times  $10^{38}$  erg s $^{-1}$ , using a distance of  $\sim 50$  kpc. This observation indicates that the TeV gamma-ray luminosity is lower than  $1 \times 10^{37}$  erg s $^{-1}$  at  $\sim 10$  TeV, which is now of a similar order to those in bright high-energy astronomical objects at various wavelengths.

The predictions concerning the emitted high-energy gamma-rays from this source have been extensively discussed (Honda and Mori 1987; Nakamura, Yamada and Sato 1987; Yamada, Nakamura, Kasahara and Sato 1988; Berezhko and Ptuskin 1989; Gaisser, Harding and Stanev 1989; Schlickeiser and Stanev 1991; Berezhko and Ksenofontov 2000). High-energy photons can be produced in collisions of accelerated particles with the ambient medium. There are several processes which could accelerate particles in young supernova remnants (see, e.g., Dogiel and Ginzburg 1989, for a review).

Gaisser, Harding and Stanev (1989) discuss the acceleration of particles at the pulsar wind shock.

However, an analysis of the 2.14 ms pulsar candidate in the remnant of SN 1987A (Middleditch et al. 2000) suggests that the magnetic field strength at the surface of a neutron star has an upper limit of  $\sim 10^{10}$  G (Nagataki and Sato 2001), which is about two orders less than typical values and that assumed by Gaisser, Harding and Stanev (1989).

The lightcurve of soft X-rays, which are expected from the interaction of the supernova shock with the matter, can be well fitted with a  $t^2$  relation (Aschenbach 2002). The recent X-ray data points tend to exceed the  $t^2$  best fit (Aschenbach 2002; Park et al. 2002). One can expect the similar behaviour of the TeV gamma-ray flux from collisions of accelerated cosmic rays with the ambient matter.

Fig. 3 shows the dependence of the gamma-ray flux with an energy  $> 3$  TeV on time since the explosion. The solid line is extracted from the results of numerical calculations by Berezhko and Ksenofontov (2000). The dashed curve is an extrapolation to that curve under the assumption that  $F_\gamma \propto t^2$ , which is a reasonable lower limit of the expected flux in the future. One can see that the our upper limit is just a factor of 3 above the theoretical prediction for the current epoch.

The presence and growing amount of synchrotron radio emission unambiguously testify to the presence of high-energy electrons accelerated by the forward-moving ejecta-driven shock. The radio spectrum has a power-law index of 0.88 (Manchester et al. 2002), which is much softer than the value of 0.5 from linear diffusive shock acceleration. This can be explained with an essential modification of the shock wave due to the very effectively accelerated nucleonic cosmic ray pressure (Berezhko and Ksenofontov 2000). Also, radio measurements show that the shock velocity has dropped from the initial value of 10000–35000 km s $^{-1}$  to  $\sim 3000$  km s $^{-1}$  (Gaensler et al. 1997), which is consistent with the shock having encountered a denser shocked component of the progenitor’s stellar wind with a number density of  $\sim 100$  cm $^{-3}$  (Chevalier and Dwarkadas 1995). It is thus reasonable to expect a considerable flux of TeV gamma-rays from the decay of  $\pi^0$  mesons produced in collisions of the cosmic ray nucleonic component with the ambient matter nuclei (Drury, Aharonian and Völk 1994; Naito and Takahara 1994), which is expected to increase

approximately by a factor of 2 between 2000 and 2006 (Berezhko and Ksenofontov 2000).

At the current rate of expansion, the shock will encounter the much denser inner optical ring in the year  $2004 \pm 2$  (Manchester et al. 2002). Thus, one can also expect a dramatic increase of the TeV gamma-ray flux, which could well exceed the current upper limits. The future detection of TeV gamma-ray emission, will unambiguously prove the idea that the main part of nucleonic cosmic rays are indeed accelerated at the supernova remnant shock waves by a diffusive acceleration process.

The next generation of southern hemisphere IACTs, CANGAROO-III and H.E.S.S., will have improved sensitivities and reduced energy thresholds. Considering the present theoretical estimations and recent radio and X-ray observations, deep observations, with a total ON-source exposure of  $\sim 100$  hours, will have a good chance of detecting a signal. A more detailed theory of high-energy gamma-ray production in the SN 1987A environment is now needed. Regular observations over the next decade are also highly desirable.

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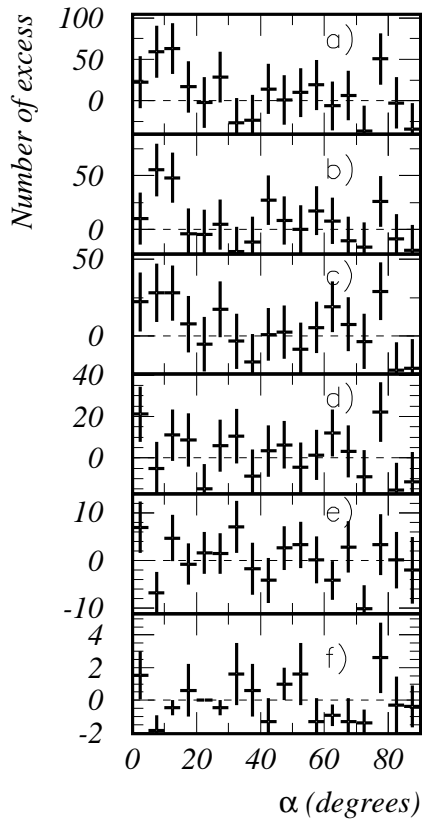


Fig. 1.— Distributions of the image orientation angle ( $\alpha$ ). These were obtained by subtracting the normalized off-source data from the on-source data. The ratio of events in the higher  $\alpha$  ( $> 20^\circ$ ) regions for the on- and off-source data was used as the normalization factor. From top (a) to bottom (f), six threshold values, as shown in Table 1, were applied to the analysis.

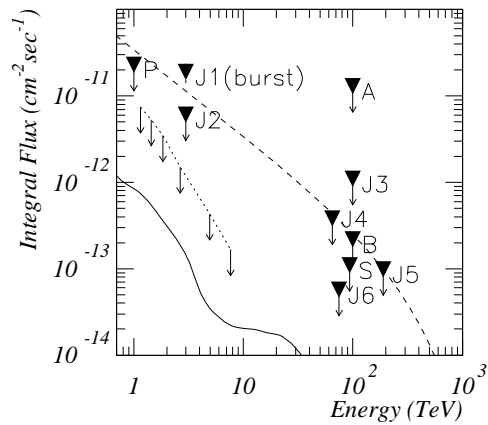


Fig. 2.— Upper limits on the flux of gamma-rays. The dotted line is that obtained by this experiment. P: Raubenheimer et al. (1988); J1–6: Bond et al. (1988a,b, 1989); Allen et al. (1993a,b); A: Ciampa et al. (1988); S: van Stekelenborg et al. (1993); B: Yoshii et al. (1996). The solid and dashed lines are theoretical predictions of the flux by Berezhko and Ksenofontov (2000); Gaisser, Harding and Stanev (1989), respectively.

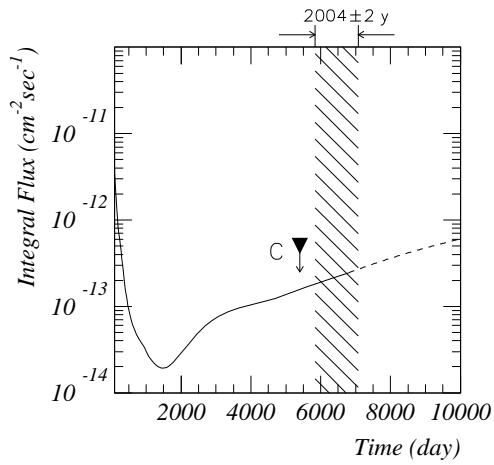


Fig. 3.— Flux of gamma-rays with energy  $E > 3$  TeV vs. time since the SN 1987A explosion. The current work upper limit (C) is shown. The solid curve was extracted from Berezhko and Ksenofontov (2000). The dashed curve is an extrapolation to the solid one. The time when the shock is expected to encounter the inner optical ring is the hatched region.

TABLE 1  
INTEGRAL FLUX UPPER LIMIT ( $2\sigma$ ).

bin number	$\gamma = 2.0$		$\gamma = 2.5$		$\gamma = 3.0$	
	$E_{threshold}$ (TeV)	$2\sigma$ -UL ( $\text{cm}^{-2}\text{s}^{-1}$ )	$E_{threshold}$ (TeV)	$2\sigma$ -UL ( $\text{cm}^{-2}\text{s}^{-1}$ )	$E_{threshold}$ (TeV)	$2\sigma$ -UL ( $\text{cm}^{-2}\text{s}^{-1}$ )
1	1.2	$7.5 \times 10^{-12}$	1.0	$1.0 \times 10^{-11}$	0.9	$1.3 \times 10^{-11}$
2	1.5	$5.3 \times 10^{-12}$	1.4	$5.8 \times 10^{-12}$	1.3	$6.5 \times 10^{-12}$
3	1.9	$3.5 \times 10^{-12}$	1.7	$3.9 \times 10^{-12}$	1.7	$3.7 \times 10^{-12}$
4	2.7	$1.5 \times 10^{-12}$	2.2	$1.8 \times 10^{-12}$	2.4	$1.4 \times 10^{-12}$
5	5.0	$4.3 \times 10^{-13}$	4.0	$4.8 \times 10^{-13}$	3.5	$5.0 \times 10^{-13}$
6	7.7	$1.7 \times 10^{-13}$	8.0	$1.3 \times 10^{-13}$	8.2	$8.5 \times 10^{-14}$