Search for γ Rays from Supernova 1987A at Energies Greater than 100 TeV

I. A. Bond,[(1)] E. Budding,[(2)] M. J. Conway,[(1)] K. B. Fenton,[(3)] H. Fujii,[(4)] Z. Fujii,[(5)] H. Hasegawa,[(6)] N. Hayashida,[(7)] M. Honda,[(7)] N. Hotta,[(8)] J. E. Humble,[(3)] S. Kabe,[(4)] K. Kasahara,[(7)] T. Kifune,[(7)] A. Masaike,[(6)] Y. Matsubara,[(7)] K. Mitsui,[(7)] Y. Miura,[(4)] M. Mori,[(6)] K. Murakami,[(5)] Y. Muraki,[(7)] M. Nagano,[(7)] K. Nakamura,[(4)] T. Nakamura,[(6)] P. M. Norris,[(1)] Y. Ohashi,[(7)] A. Okada,[(7)] To. Saito,[(9)] M. Sakata,[(9)] H. Sato,[(6)] S. Shibata,[(5)] M. Shima,[(9)] J. R. Storey,[(1)] T. Tanimori,[(4)] M. Teshima,[(10)] S. Torii,[(11)] K. Uchino,[(4)] Y. Watase,[(4)] M. D. Woodhams,[(1)] Y. Yamamoto,[(9)] P. C. M. Yock,[(1)] and T. Yuda[(7)]

(The JANZOS Collaboration)

[(1)]*Department of Physics, University of Auckland, Auckland, New Zealand*
[(2)]*Carter National Observatory of New Zealand, Wellington, New Zealand*
[(3)]*Department of Physics, University of Tasmania, Hobart 7001, Australia*
[(4)]*National Laboratory for High Energy Physics (KEK), Tsukuba 305, Japan*
[(5)]*Cosmic Ray Research Laboratory, Nagoya University, Nagoya 464, Japan*
[(6)]*Department of Physics, Kyoto University, Kyoto 606, Japan*
[(7)]*Institute for Cosmic Ray Research, University of Tokyo, Tokyo 188, Japan*
[(8)]*Department of Physics, Utsunomiya University, Utsunomiya 321, Japan*
[(9)]*Department of Physics, Konan University, Kobe 658, Japan*
[(10)]*Department of Physics, Tokyo Institute of Technology, Tokyo 152, Japan*
[(11)]*Department of Physics, Kanagawa University, Yokohama 221, Japan*
(Received 19 January 1988)

We searched for ultrahigh-energy γ rays emitted by Supernova 1987A with a new cosmic-ray facility installed at the Black Birch Range in New Zealand. The observations from 13 October to 3 December 1987 suggest no clear clustering of events around the direction of the supernova. We conclude that an upper limit on the flux of γ rays of energies greater than 100 TeV is 1.1×10^{-12} cm^{-2} s^{-1} (95% confidence limit) for a differential spectral index $\alpha=2.0$ and source distance $d=50$ kpc. This value gives an upper bound on the γ-ray luminosity of the supernova of 5.5×10^{38} erg s^{-1} for 10^{14}–10^{17} eV.

PACS numbers: 97.60.Bw, 95.85.Qx

The supernova 1987A in the Large Magellanic Cloud (LMC) has provided the first opportunity to study the emission of particles and electromagnetic radiation of various wavelengths from a young supernova. The detection of neutrino bursts by the Kamiokande II and IMB (Irvine-Michigan-Brookhaven) detectors[1,2] suggested the formation of a neutron star at the center of the expanding ejecta.[3] A rapidly rotating, magnetized neutron star may be a powerful source of ultrahigh-energy (UHE) cosmic rays. Sato,[4] Berezinsky and Prilutsky,[5] and Shapiro and Silberberg[6] have pointed out that high-energy γ rays and neutrinos may be produced from the decay of pions generated by the collisions of hadrons accelerated by the neutron star with supernova ejecta. The detection of these UHE γ rays should provide important knowledge about the origin of cosmic rays and their acceleration mechanism. The flux of γ rays should increase with time as the column density of the expanding shell decreases, until it reaches some optimal value. The same mechanism will produce high-energy neutrinos, which can be detected in underground detectors from the observations of neutrino-induced upward-going muons.[7] The Kamiokande II group observed no such muons from the direction of the supernova in the six months following the explosion and placed a limit on the neutrino luminosity of 1.6×10^{41} erg s^{-1} for a spectral index $\alpha=2.1$, a cutoff energy 10^{15} eV, and the distance to LMC 50 kpc.[8] The upper limit on UHE γ-ray flux[9] deduced from this result is 1×10^{-10} cm^{-2} s^{-1}. Direct observations of γ rays should provide a more sensitive measurement of the cosmic-ray luminosity of the supernova. γ rays emerge in a later stage,[10,11] with the maximum intensity occurring about a half to one year after the supernova explosion,[12-14] and the observation of γ rays in this time period is the motivation of the present experiment.[15]

Photon-photon collisions with the cosmic microwave background radiation of 2.7 K reduce the UHE γ-ray flux as it traverses the distance from LMC to the Earth.[16] The absorption of γ rays becomes effective at energies higher than about 200 TeV and reaches its maximum value at 2500 TeV. Thus the detection sensitivity for γ rays of energy less than 200 TeV is important in this work.[17] We designed two types of detectors to observe these γ rays. One is a surface air-shower array with close spacing and good angular resolution for the

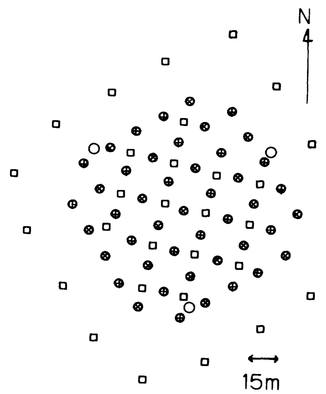

FIG. 1. The arrangement of detectors on the Black Birch Range. Circles with crosses and circles with plusses, two groups of 0.5-m^2 detectors; squares, 1-m^2 detectors; open circles, mirrors.

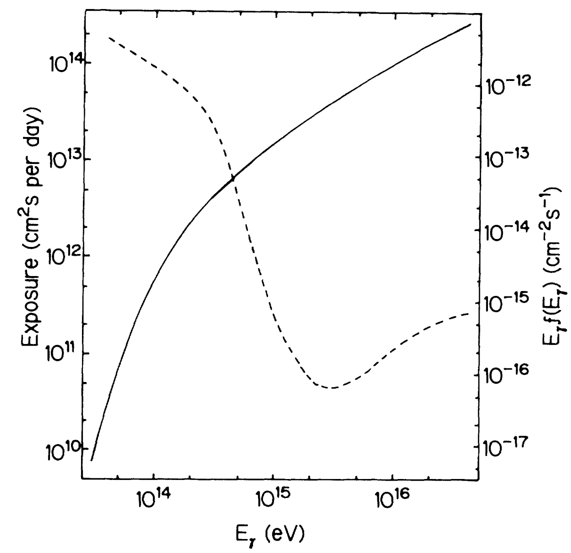

FIG. 2. Effective exposure of the array vs γ-ray energy (solid line, left scale), and differential γ-ray flux (dashed line, right scale), which is normalized to our upper limit written in the text. $\alpha = 2.0$ and $d = 50$ kpc are assumed.

100-TeV region and the other is a mirror system to detect atmospheric Čerenkov light for the 1-TeV region. Contemporal observation of the two energy regions may provide useful information on the energy spectrum and the emission mechanism of UHE γ rays. This Letter is a report on the first result of the array system. The mirror system and the results gained with it will be reported in a separate paper.

The instruments are installed at the Black Birch Range in New Zealand (1640 m above sea level, 41°45′S, 173°47′E). The array consists of 76 scintillation detectors. Square-plate scintillators are housed in pyramidal enclosures. Forty-five of the scintillators are of 0.5 m^2 in area and 5 cm in thickness. They are viewed from below by fast 2-in. photomultipliers (Hamamatsu Photonics model H1949) from a distance of 50 cm. A lead sheet of 5 mm thickness is placed on each of these scintillators to convert γ rays in air showers to electron pairs. The other 31 scintillators are 1×1 $m^2\times10$ cm and viewed from above, at a distance of 103 cm, by 5-in. photomultipliers (Hamamatsu Photonics model R877). These are used for particle-density measurements. The detector arrangement is shown in Fig. 1. The signal of each 0.5-m^2 detector is used for measurement of particle density by use of an analog-to-digital converter and the time of the passage of the shower front with a time-to-digital converter of 125-ps resolution. The timing signal is available for those detectors for which the output is larger than 0.3 times the single minimum-ionizing particle signal. Measurement of the relative delay times of the 0.5-m^2 detectors and the recording electronics is carried out with cosmic-ray muons selected by a 20×20-cm^2 scintillation detector. The measured timing resolution is 1.2 ns (1 standard deviation). The signal of each 1-m^2 detector is recorded with an analog-to-digital converter only.

The recording system is triggered by any fourfold coincidence of the 0.5-m^2 detectors within a 150-ns time interval. The discrimination level for each detector for a trigger is 1.8 times the single-particle level. A computer (NEC PC-9801VX) under MS-DOS operating system is used to transfer data from modules through a CAMAC dataway. Data are stored on write-once optical disks of 800-megabyte capacity.

The observations started on 13 October 1987 and 3.88×10^6 events were accumulated by 3 December 1987. The effective running time for this period is 34.6 days. The trigger rate is about 1 Hz. The effective exposure (defined as the product of effective area and time) was calculated by detailed Monte Carlo simulations[18] for γ rays from the direction of the supernova and is shown in Fig. 2 for one day of observation. γ rays with energies above about 40 TeV will be recorded.

The arrival direction of each air shower is computed by our determining the shower front from the timing signal in the 0.5-m^2 detectors. In this procedure, the shower-front structure is approximated as a plane. A weighted mean is taken in the fit so that detectors with larger signals are given more significance. The angular resolution is estimated as follows. The 0.5-m^2 detectors are divided into two groups as is shown in Fig. 1. Each group of detectors is used to reconstruct each arrival direction. We define ψ, a measure of the angular accuracy, as the space angle between these two directions and determine ψ as a function of Σ, the sum of analog-to-digital converter values of the 0.5-m^2 detectors. (One minimum ionizing particle contributes about 100 to Σ). Figure 3 shows the distribution of ψ as a function of Σ. The three curves in the figure are contours within which 20%, 50%, and 80% of events are contained. The angular resolution, which is defined as the radius of a circle

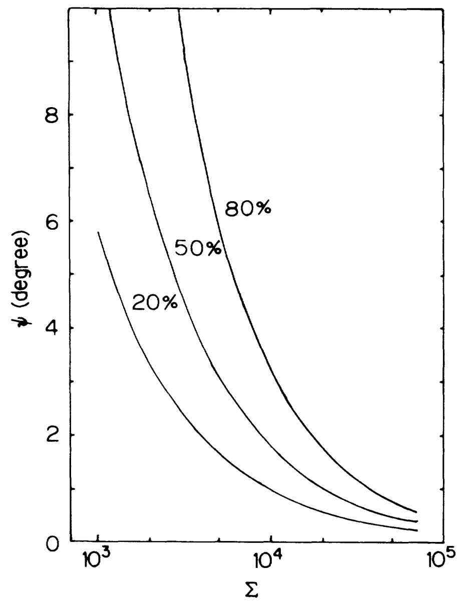

FIG. 3. The distribution of ψ as a function of Σ. Three curves which contain 20%, 50%, and 80% of events are shown.

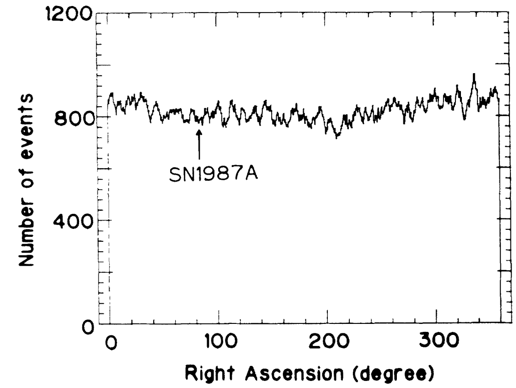

FIG. 4. Right-ascension scan of events near the declination of the supernova. Each point represents the number of events within the angular-resolution angle of 1.73° and separated by $\frac{1}{4}$ of the resolution angle in right ascension.

within which 50% of events fall, is estimated as $\Delta\theta \approx \frac{1}{2}\bar{\psi}$, where $\bar{\psi}$ is the median value of ψ. (A factor $1/\sqrt{2}$ comes from the subtraction of two directions and another $1/\sqrt{2}$ comes from statistics). $\Delta\theta$ is well expressed as

$$\Delta\theta = 0.9° (\Sigma/10^4)^{-0.80}.$$

The peak value of the Σ spectrum is about 3×10^3. We discard events with $\Sigma < 2\times10^3$ (9.5% of total events) as they have large errors in their directions.

Figure 4 represents a right-ascension scan of events near the declination of the supernova. We define the angular window as a circle of radius 1.73° centered at declination $-69.3°$ and right ascension $84.0° + 1.73° j/4$, where j are integers to specify data sets from various directions. The radius of the circles, 1.73°, is chosen to maximize the ratio $N_S/\sqrt{N_B}$, where N_S is the number of signals and N_B is the number of background showers, and to contain 53% of signals from the source. No clear excess appears.

An upper limit on the flux of UHE γ rays is obtained with the maximum-likelihood method. Ten nonoverlapping data sets near the supernova ($j = -20, -16, \cdots, -4, 4, \cdots, 20$) are taken to estimate the number of background cosmic-ray showers.[19] This procedure is relatively insensitive to the nonuniformity of observation time in right ascension. The 95% confidence-level upper-limit result for N_S is 49 events. The effective exposure is 2.54×10^{13} cm^2 s for the γ rays above 40 TeV from the supernova calculated from the spectrum with the assumption of a spectral index $\alpha = 2.0$ and complete absorption by the microwave background radiation (see Fig. 2). These values give the upper limit on the integral flux of UHE γ rays above 100 TeV as 1.1×10^{-12} cm^{-2} s^{-1} (95% confidence limit). The UHE γ-ray luminosity of the supernova is given by

$$L_\gamma(E_\gamma = 10^{14}\text{-}10^{17}\ \text{eV}) \le 5.5\times10^{38}[d/(50\ \text{kpc})]^2\ \text{erg s}^{-1},$$

where d is the distance to LMC.

The intensity of UHE γ rays observed at Earth may, with various models, be related to a presumed proton flux at the source. The expected event number for our total exposure is tabulated in Table I. Yamada *et al.*[13] calculated the γ-ray flux assuming 10^{17}-eV monoenergetic proton injection of a total power (L_p) of 10^{41} erg s^{-1} and complete absorption by the background radiation, taking the source distance (d) as 56 kpc. The expected event number is derived from the γ-ray spectrum at a shell thickness 76.3 g cm^{-2} (where the UHE γ-ray flux reaches its maximum value) and is normalized at $d = 50$ kpc. Gaisser, Harding, and Stanev[14] assumed an $E^{-2}dE$ proton spectrum with a cutoff at 10^{17} eV and $L_p(\ge 10^9\ \text{eV}) = 10^{40}$ erg s^{-1} at $d = 50$ kpc. The γ-ray spectrum can be regenerated by electron inverse Compton scattering on the background radiation if the average

TABLE I. Expected number of events and upper limits on cosmic-ray luminosity (L_p) of Supernova 1987A based on some models. See text for detail.

Model	Expected events	Upper limit L_p (erg s^{-1})
Yamada *et al.*[a]	526	1.4×10^{40}
Gaisser *et al.*[b] (cascading)	358	2.6×10^{39}
(no cascading)	173	5.3×10^{39}

[a]Reference 13.
[b]Reference 14.

intervening field is $\ll 10^{-10}$ G,[20] and so two event numbers, with and without this cascading effect, are computed. We can place upper limits on L_p for these models as shown in Table I.

In conclusion, we have placed an upper limit on the UHE γ-ray luminosity of Supernova 1987A at 5.5×10^{38} erg s^{-1} above 100 TeV and this corresponds to the cosmic-ray luminosity of 2.6×10^{39}–1.4×10^{40} erg s^{-1} depending upon various models. This result places a restriction on models which assume a very active process in Supernova 1987A as a source of UHE cosmic rays.[4,21,22]

We are grateful to Professor J. Arafune, Professor H. Sugawara, and Professor M. Fujimoto for their support of our experiment. We thank Dr. D. Robinson for his hospitality in the Black Birch site. We also acknowledge the cooperation of the New Zealand Ministry of Works and Development (Blenheim Branch). This work is supported in part by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture, Japan, Inamori foundation, Japan, Inoue foundation, Japan, the Japan–New Zealand foundation, the University of Auckland Research Committee, the New Zealand Scientific Research Distribution Committee, and the New Zealand University Grants Committee. Part of the analysis was carried out by FACOM M380 at the Computer Room of the Institute for Nuclear Study, University of Tokyo.

[1]K. Hirata *et al.*, Phys. Rev. Lett. **58**, 1490 (1987).

[2]R. M. Bionta *et al.*, Phys. Rev. Lett. **58**, 1494 (1987).

[3]K. Sato and H. Suzuki, Phys. Lett. B **196**, 267 (1987).

[4]H. Sato, Prog. Theor. Phys. **58**, 549 (1977).

[5]V. S. Berezinsky and O. F. Prilutsky, Astron. Astrophys. **66**, 325 (1978).

[6]M. M. Shapiro and R. Silberberg, in *Relativity, Quanta and Cosmology,* edited by F. DeFinis (Johnston Reprint Corporation, New York, 1979), Vol. 2, p. 745.

[7]T. K. Gaisser and T. Stanev, Phys. Rev. Lett. **58**, 1695 (1987), and **59**, 844(E) (1987).

[8]Y. Oyama *et al.*, Phys. Rev. Lett. **59**, 2604 (1987).

[9]M. Honda and M. Mori, Prog. Theor. Phys. **78**, 963 (1987).

[10]H. Sato, Mod. Phys. Lett. A **2**, 801 (1987).

[11]V. S. Berezinksy and V. L. Ginzburg, Nature (London) **329**, 807 (1987).

[12]T. Nakamura, Y. Yamada, and H. Sato, Prog. Theor. Phys. **78**, 1065 (1987).

[13]Y. Yamada, T. Nakamura, K. Kasahara, and H. Sato, Prog. Theor. Phys. **79**, 416 (1988).

[14]T. K. Gaisser, A. Harding, and T. Stanev, Nature (London) **329**, 314 (1987).

[15]Japan–Australia–New Zealand Observation of Supernova 1987A (JANZOS) Collaboration, *Proposal for Detection of Ultra-High-Energy Gamma-Rays from Supernova 1987A* (Institute for Cosmic Ray Research, University of Tokyo, Tokyo, April 1987).

[16]R. J. Gould and G. P. Schréder, Phys. Rev. **155**, 1404 (1969).

[17]Ciampa *et al.* searched for UHE γ rays using the Buckland Park air-shower array (35°S) for six months following the explosion, and observed no clear excess. However, their detection threshold is somewhat below 1000 TeV, so that absorption by the microwave background radiation is effective. D. Ciampa *et al.*, Adelaide University Report No. ADP-87-33-E/15, 1987 (to be published).

[18]K. Kasahara, S. Torii, and T. Yuda, in *Proceedings of the Sixteenth International Cosmic Ray Conference, Kyoto, Japan, 1979,* edited by S. Miyake (Institute for Cosmic Ray Research, University of Tokyo, Tokyo, 1979), Vol. 13, pp. 70 and 76; K. Kasahara *et al.*, to be published.

[19]R. J. Protheroe, Astron. Expr. **1**, 33 (1984).

[20]R. J. Protheroe, Mon. Not. Roy. Astron. Soc. **221**, 769 (1986).

[21]D. Eichler and J. R. Letaw, Nature (London) **328**, 783 (1987).

[22]T. K. Gaisser, T. Stanev, and F. Halzen, University of Wisconsin-Madison Report No. MAD/PH/377, 1987 (unpublished).