Search for TeV γ rays from SN 1987A during December 1987 and January 1988

I. A. Bond,[1] E. Budding,[2] M. J. Conway,[1] K. B. Fenton,[3] H. Fujii,[4] Z. Fujii,[5] M. Fujimoto,[6] H. Hasegawa,[7] N. Hayashida,[8] M. Honda,[8] N. Hotta,[9] J. E. Humble,[3] S. Kabe,[4] K. Kasahara,[8] T. Kifune,[8] A. Masaike,[7] Y. Matsubara,[8] K. Mitsui,[8] Y. Miura,[4] M. Mori,[4] K. Murakami,[5] Y. Muraki,[8] M. Nagano,[8] K. Nakamura,[4,8] T. Nakamura,[7] P. M. Norris,[1] Y. Ohashi,[8] A. Okada,[8] To. Saito,[10] M. Sakata,[10] H. Sato,[7] S. Shibata,[5] M. Shima,[10] J. R. Storey,[1] T. Tanimori,[4] M. Teshima,[11] S. Torii,[12] K. Uchino,[4] Y. Watase,[4] M. D. Woodhams,[1] Y. Yamamoto,[10] P. C. M. Yock,[1] and T. Yuda[8]

(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]*Tokyo Astronomical Observatory, University of Tokyo, Tokyo 181, Japan*
[7]*Department of Physics, Kyoto University, Kyoto 606, Japan*
[8]*Institute for Cosmic Ray Research, University of Tokyo, Tokyo 188, Japan*
[9]*Department of Physics, Utsunomiya University, Utsunomiya 321, Japan*
[10]*Department of Physics, Konan University, Kobe 658, Japan*
[11]*Department of Physics, Tokyo Institute of Technology, Tokyo 152, Japan*
[12]*Department of Physics, Kanagawa University, Yokohama 221, Japan*
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Very-high-energy γ rays emitted by the supernova 1987A were searched for at the Black Birch Range in New Zealand during December 1987 and January 1988. Data obtained in 42 hours of observation time give an upper bound on the flux at the 95% confidence level of 6.1×10^{-12} cm^{-2} s^{-1} for γ rays with energies above 3 TeV. Data obtained on 14 and 15 January are found to have excess counts, above the background level, corresponding to a flux of $(1.9\pm0.5)\times10^{-11}$ cm^{-2} s^{-1} and a total energy of $\sim10^{43}$ ergs.

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A number of observations of supernova 1987A in the Large Magellanic Cloud (LMC) are underway. It may be possible to detect signals of energetic processes taking place in the supernova. Particles accelerated to high energies by a rapidly rotating neutron star are expected to produce energetic γ rays.[1] High-energy particles may also be generated by a shock mechanism when the supernova ejecta collide with circumstellar matter.[2]

A collaboration of Japan, Australia, and New Zealand (JANZOS) started in late 1987 to monitor PeV and TeV γ-ray emission by SN 1987A at the Black Birch Range in New Zealand at latitude 41.8° S and altitude 1640 m. The PeV observations (> 100 TeV) did not show a signal from the supernova for the first 1.5 month's data.[3] The present paper describes results obtained in the TeV region in December 1987 and January 1988 by detecting Čerenkov light emitted by showers of particles produced by γ rays when they strike the upper atmosphere. The total viewing time reported here is 42 hours.

The apparatus is an array of three spherical aluminum mirrors. Each mirror, of 2-m aperture and of 2-m focal length, is at the vertex on an 80-m triangle. The supernova is observed, at an almost constant value of zenith angle, through its meridian passage in the "drift scan mode" with fixed mirrors.[4] Ten fast phototubes (Hamamatsu H1531) with high-gain first dynodes of GaAs, arranged in the focal plane of each mirror, view a strip of sky along the path of SN 1987A. Each phototube sees an area of sky 2.3°×2.3°. Absolute gains, measured by single photoelectron response, are set at 2×10^5. A trigger is produced when any one of the ten sets of three phototubes, seeing the same direction in the sky and mounted in three different mirrors, has coincident signals. The total trigger rate from all ten sets is about 4 Hz.

The output of each phototube is fed into analog-to-digital (ADC) and time-to-digital (TDC) converters. The ADC outputs are used to estimate the energies of γ rays and cosmic rays. The median energy for detectable γ rays is estimated by Monte Carlo simulations[5] to be 3 TeV. The effective detection area of the apparatus can be calculated from the cosmic-ray background frequency and is estimated to be 3×10^8 cm^2. The overall accuracy of the timing signals is measured with a pulsed laser system and found to be better than 1 ns. The timing signals in the three mirrors are used to infer the arrival direction of a cosmic ray or γ ray by determining the front of the Čerenkov light disk.[6-8] The angular resolution is estimated by simulations[6,7] to be about 0.5° (FWHM). The resolution depends on the diffuseness of the front of the light disk. By examining events in which neighboring phototubes [at neighboring right ascensions (RA's)] in a mirror are struck, we find an effective diffuseness of 3.2 ns (FWHM). For these events in which there are multiple hits in a mirror we use the earliest TDC value to reconstruct the shower direction, and we assume the resulting angular resolution is about 0.5° in the direction of RA and 1.0° in declination.

In order to compensate for the effect of variable background illumination caused by stars, a light-emitting diode (LED) controlled by a negative feedback circuit with a time constant ~ 3 s[7] illuminates each phototube to keep the dc current constant (~ 40 μA, larger than 30 μA corresponding to the brightest region of the LMC). The anode current and the counting rate of every phototube is monitored and recorded. The variation of dc current of the phototubes was measured, with the LED feedback system disabled, when the star β Car transited the field of view of the telescope to infer the overall gain of the apparatus and to calibrate the pointing attitude of each mirror with an accuracy of about 0.3° in hour angle.

The directions of the triggered events accumulated over half an hour are plotted in Fig. 1 as a function of zenith angle and azimuth, a coordinate system fixed to the Earth. The path of SN 1987A is indicated by the solid curve. The concentration of events around the path of the supernova implies that almost all triggers are caused by high-energy cosmic rays. In our analysis we use data within $\pm 0.5°$ of the declination of SN 1987A and the contamination of chance coincidences due to background light is about 0.1%. The distribution of events as a function of ϕ, $f_1(\phi)$, where ϕ denotes hour angle, is proportional to the directional response of the system. The response of the system may also vary with time because of changing sky conditions. This is monitored by $f_2(t)$, the trigger rate at time t. These directional and time variations are inferred from all the data including the off-source data, 40–50 times more abundant than the on-source after the timing analysis. The product of f_1 and f_2 is defined as the expected number of counts as a function of ϕ and t, being the average number of cosmic-ray background events corrected for the angular response of the system and time-dependent sky conditions. The great number of off-source events, about 4×10^4 per night, determines the level of cosmic-ray background events to an accuracy better than 1%.

The ratio of observed to expected events is examined to search for any excess beyond the uniform distribution of the off-source background of cosmic rays. The total number of events used for the analysis is about 560000. Figure 2 shows the distribution of observed events in the declination strip $-69.3° \pm 0.5°$ as a function of RA with all the observations of 42 hours included. The smooth curve indicates the expected events. The bin width is 1.5° in RA, successively shifted by 0.5° in an overlap of 1.0° with the neighboring bins. There exists no significant excess in the direction of SN 1987A (84.0° in RA). The bin width of 1.5° in RA corresponds to about 0.5° in the actual angular spread. This is, approximately, the angular resolution of the system. To determine an upper bound on the γ-ray flux we include events within 4.5° in RA. This yields an upper bound on the

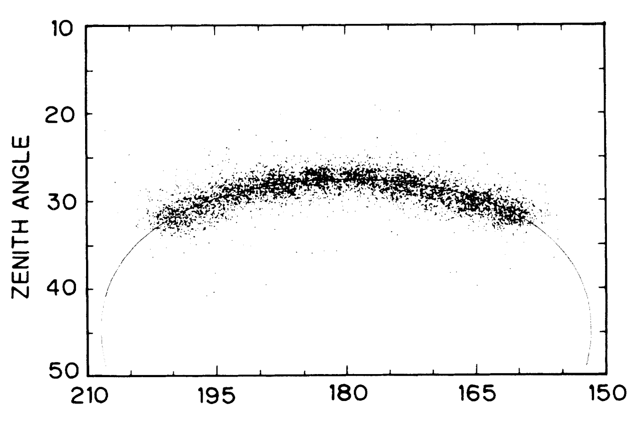

FIG. 1. The incident directions of the triggered events are reconstructed from the timing data and are plotted as a function of zenith angle and azimuth, a coordinate system fixed to the earth. The solid curve designates the path of SN 1987A.

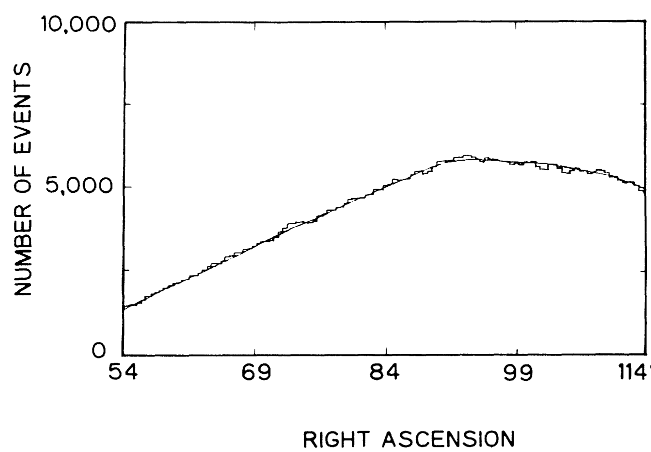

FIG. 2. The observed counts during the total 42 hours are plotted as a function of RA in the declination strip $-69.3° \pm 0.5°$. The smooth curve indicates the expected one, i.e., the average level of cosmic-ray background. The bin width is 1.5° in RA, successively shifted by 0.5° in an overlap of 1.0° with the neighboring bins.

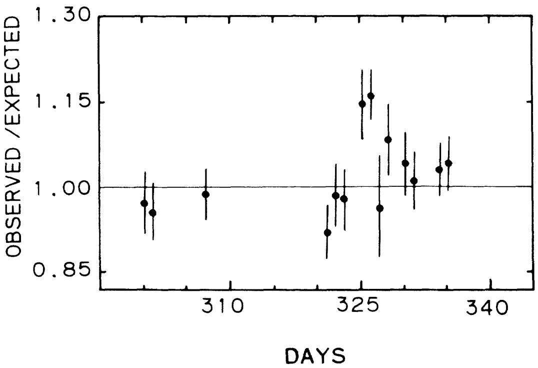

FIG. 3. The excess during each night of observation is plotted as a function of days after the supernova explosion. The vertical axis is the ratio of the observed to expected counts.

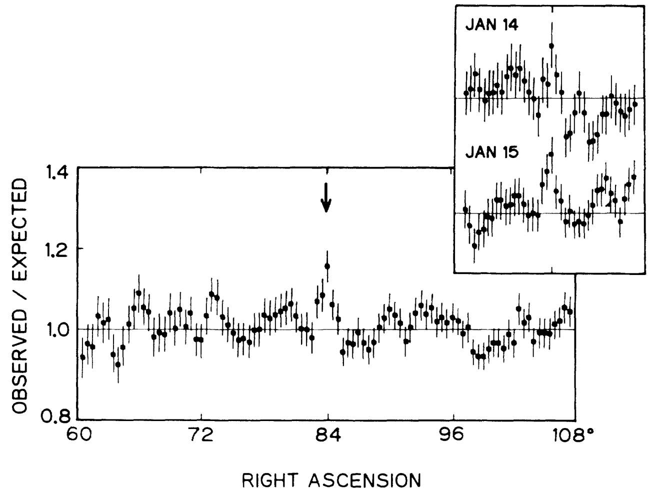

FIG. 4. The ratio of observed to expected counts is plotted as a function of right ascension for the combined data sets of 14 and 15 January. The bin width is 1.5° in right ascension overlapping 1.0° with neighboring bins. The SN 1987A is at 84.0° in RA as indicated by an arrow. The separate data of each night are inserted in the figure.

γ-ray flux, at the 95% confidence level, of 6.1×10^{-12} cm^{-2} s^{-1} for energies greater than 3 TeV during the period December 1987 to January 1988, whereas an upper limit of 2.3×10^{-11} cm^{-2} s^{-1} for energies greater than 1 TeV was reported by Raubenheimer *et al.* for November 1987.[9] Our limit on the γ-ray luminosity above 3 TeV for December 1987 and January 1988 is 8.4×10^{37} ergs s^{-1}. This assumes an E^{-2} γ-ray spectrum with a cutoff at 10^{17} eV and a distance to SN 1987A of 50 kpc.

The excess during each night of observation is plotted in Fig. 3 as a function of post supernova days. The vertical axis is the ratio of observed to expected events in a 1.5° RA band centered at the direction of SN 1987A. The data of 14 and 15 January are found to have 2.2σ and 3.3σ excesses, respectively. The ratio is plotted against RA in Fig. 4 for the combined data of the two nights of observation, showing an excess of 3.9σ following the method of Li and Ma.[10] The data in each night are also inserted in the figure. In the supernova bin the observed number of events is 767 while 663.3 ± 3.9 events are expected from cosmic-ray background. The number of off-source events is 28 800.

The distribution of deviations from the expected constant background level is found to fit well with the normal error function. The consecutive excesses in January suggest that a burst of γ-ray emission may have occurred. We calculated by Monte Carlo simulations the chance probability of the data producing an apparent burst with a statistical significance of 3.9σ and lasting for one or more days. The chance probability was found to be 1.6×10^{-3}. Consequently, we do not exclude the possibility that the observed excess was a statistical effect. We hope that more elaborate high-energy observations may be made of this interesting object in the future.

If a burst of very-high-energy γ rays was emitted by the supernova then the flux and energy of emission may be calculated as follows. The data for 14 and 15 January correspond to a flux of $(1.9\pm0.5)\times10^{-11}$ cm^{-2} s^{-1} for $E_\gamma \gtrsim 3$ TeV. This implies a luminosity of

$$(8.7\pm2.2)\times10^{37}[1+\ln(E_{max}/10^{14}\,\mathrm{eV})/3.5]\ \mathrm{ergs\ s^{-1}}$$

assuming an E^{-2} differential γ-ray spectrum and integrating between 3 TeV and cutoff energy E_{max}. If we assume a duration of 2–3 days for the excess then the total energy emitted in TeV γ rays is

$$(1.9\pm1.1)\times10^{43}[1+\ln(E_{max}/10^{14}\,\mathrm{eV})/3.5]\ \mathrm{ergs}.$$

An interesting feature of the present result is that the observed time of the excess coincides closely with the central time of the 20-day x-ray flare detected by the Ginga satellite.[11] The total energy in x-ray emission is reported to be $\sim10^{43}$ ergs, comparable to the value which the present excess suggests.

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