# Search for Photons of Energy > 50 TeV from SN 1987A in Early 1988

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We report analysis of data from the South Pole Air Shower Experiment taken in January and February 1988 while the array was being commissioned. These first results are already of interest because they lead to a limit on an air-shower signal from SN 1987A comparable to the best existing limit and also because the supernova produced a high x-ray flux and a possible TeV signal during that period.

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The South Pole Air Shower Experiment (SPASE) was proposed to search for possible sources in the southern sky[1] of ultrahigh-energy $\gamma$ rays, such as x-ray binaries, from the U.S. Amundsen-Scott Station. For an array on the rotation axis of the Earth any potential source will always be at the same zenith angle and will therefore be observed against a constant background of cosmic-ray-induced showers. This is of particular value for sources that may themselves be variable. In contrast, at normal latitudes, the background varies as the source rises and sets, and there are most likely long periods each day when it is too low for viewing altogether.

The occurrence of supernova 1987A at declination $-69°$ presented a new target of opportunity in an ideal direction for viewing from the geographic South Pole. Since young supernova remnants are among the candidates for sources of cosmic rays with energies up to thousands of TeV,[2-8] we have the opportunity to search for signals of particle acceleration and interaction in this new supernova remnant. Detection of secondary photons would identify the supernova remnant as a cosmic accelerator and beam dump.

The array[9] consists of sixteen detectors each of 1-m$^2$ area at fourteen locations on a 30-m triangular grid. The trigger condition is that at least five out of fourteen scintillators have a signal above a discriminator threshold equivalent to 1.3 minimum ionizing particles. The resulting trigger rate is $\approx 1$ shower per second. Because of the high altitude of the site, the resulting threshold is about 50 TeV, well below the energy ($\sim$250 TeV) above which photons from the 50-kpc distance to SN 1987A would be attenuated by $\gamma\gamma \rightarrow e^+e^-$ in the background radiation.

The array was deployed in December 1987 and became fully operational on 21 December. During the initial phase of startup and testing in January and February 1988, over $2\times10^6$ events were recorded, and these data were brought out on tape before transportation to the South Pole stopped for the Austral winter. Subsequently, SPASE has been operating nearly continuously (95% duty factor), but the bulk of the data are not yet available. Meanwhile, because of widespread interest in SN 1987A, we report here analysis of the data as summarized in Table I.

Because of fluctuations in shower development, air-shower arrays do not have sharp energy thresholds. At a

TABLE I. Summary of data analyzed.

| Date (1988) | Day after SN 1987A | Events ($10^6$) |
|---|---|---|
| 3-13 Jan. | 314-324 | 0.58 |
| 16 Jan. | 327 | 0.04 |
| 20-27 Jan. | 331-338 | 0.24 |
| 29 Jan.-1 Feb. | 340-343 | 0.22 |
| 3-10 Feb. | 345-352 | 0.39 |
| 12-14 Feb. | 354-356 | 0.22 |
| Totals | 449 h | 1.69 |
| | | (1.07 contained) |

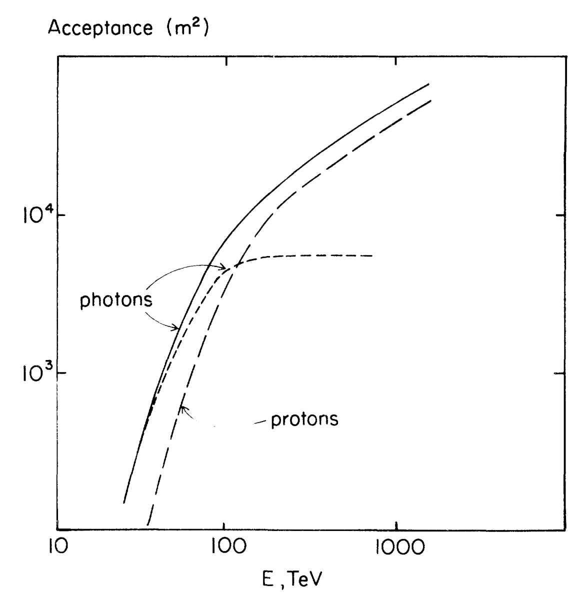


FIG. 1. Effective area $A_{\rm eff}$ as a function of primary energy for protons and for photons. The dashed line for photons is for shower cores that land inside the array.

given trigger setting an array is occasionally triggered by deeply penetrating small showers that happen to land in the most sensitive regions of the array. Sufficiently energetic (therefore large) showers, on the other hand, can sometimes trigger the array when their cores fall outside. To determine the flux from a source, or a limit, it is therefore necessary to determine the effective area $A_{\rm eff}(E)$ of the array as a function of energy $E$ of the incident photon. We have made two independent calculations of the effective area of SPASE, which both give the same result, illustrated in Fig. 1 for the zenith angle of SN 1987A, 21°. In both cases there is first a calculation for showers induced by cosmic rays, which is normalized or checked against details of the measured counting rate. Then a calculation of effective area for photon-induced showers is made. Since only showers with fitted cores inside the array are used for the search for a signal from SN 1987A, we show the calculated effective area for photon showers separately for all events and for cores inside the perimeter.

As a result of the strong energy dependence of the effective area, any signal will depend on the shape as well as the magnitude (energy content) of the spectrum of photons from the source. For a known spectrum, one would obtain the expected signal by folding the acceptance, calculated for the direction of the source, with the spectrum. Of course, the spectrum is not known in advance, but must be determined by observation—if a signal is seen. It is also possible to determine limits in a relatively model-independent way, as will be discussed below.

For illustration, we consider two possible, but rather different differential source spectra of photons: (1) the result of a power-law parent-proton spectrum with differential index −2 and cutoff above 100 PeV [5,8] and (2) the photon spectrum that results from a monoenergetic proton spectrum of energy 100 PeV.[10] The first example produces a power-law photon spectrum at the source with the same spectral index as the parent spectrum for photon energies much less than the cutoff of the parent spectrum. The resulting photon spectra at Earth for these two examples are shown in Fig. 2 after attenuation in the intervening background radiation (including the effect[10] of the short-wavelength excess above the 3° blackbody radiation recently reported by Matsumoto *et al.*[11]). For both examples, the normalization at the source is $10^{39}$ ergs/s in protons inside the supernova.

In Fig. 3, we show the distribution of energies of photons that trigger the array for the spectra of Fig. 2. By comparing the expected signal for a given spectrum (which is the area under the curve of Fig. 3) with the

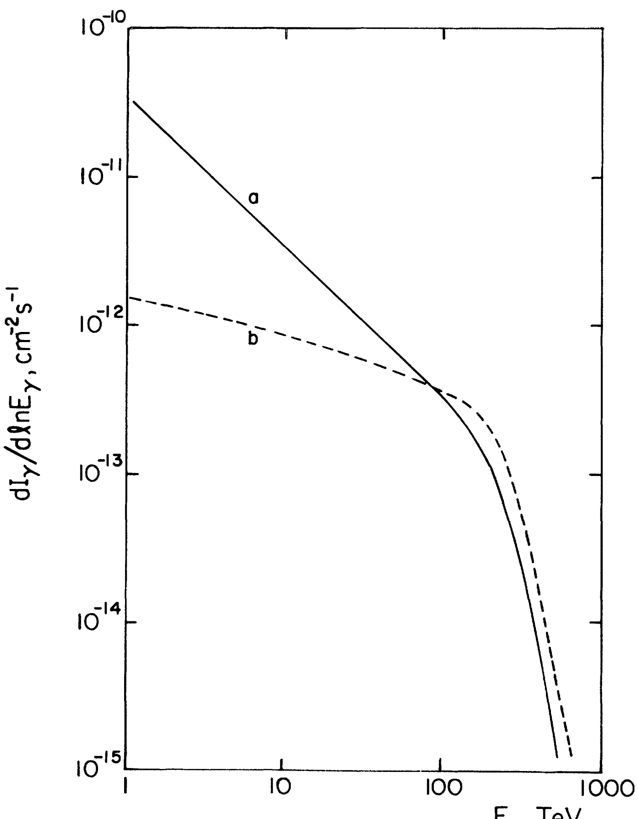


FIG. 2. Photon spectra at Earth for two simple models of photon production by accelerated protons at SN 1987A: *a*, differential proton spectrum proportional to $E^{-2}$ up to $10^5$ TeV, and *b*, monoenergetic proton at $10^5$ TeV. Normalization corresponds to $10^{39}$ ergs/s in protons for both cases.

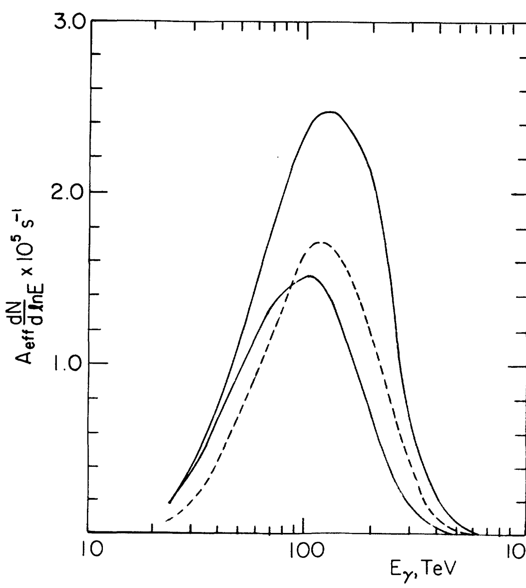


FIG. 3. Distribution of energies of photons that trigger the array for the two spectra of Fig. 2. The solid curves correspond to model *a* of Fig. 2 and the dashed curve to model *b*. The upper curve for model *a* is for all triggers. The other two curves are for showers with cores within the array perimeter.

number of events in the angular bin that contains the supernova, it is possible to convert the observed flux (or the upper limit if no excess is observed) into power in accelerated particles at the source for the particular model. This is useful as a way of making a standard comparison between various experiments that are sensitive to different regions of energy.

We want to emphasize that a single measure of flux (or a limit) can be obtained that is almost independent of the spectral shape *provided* it is evaluated near the median energy of the detected showers. For the two rather different spectra of Fig. 2, the median energies are 90 and 110 TeV. The ratios of counting rate to differential intensity at 100 TeV are 7690 $m^2$ for curve *a* of Fig. 3 and 7250 $m^2$ curve *b*, only 6% different. (Differential intensity is defined here as $dI/d\ln E$ per unit area per unit time.)

The other critical factor in searching for a signal from a point source is the angular resolution of the array, which also depends on shower energy and core location. The isotropic background of cosmic-ray showers decreases quadratically as the angular uncertainty decreases. We have used two independent fitting programs to assign shower directions.[9] In this first analysis we use an angular uncertainty of $\psi = 1.5°$, where $\psi$ is the rms uncertainty in space angle. For simplicity, we use a square search window. The optimum signal-to-noise ratio is then obtained (assuming Gaussian errors in space angle) for a $3° \times 3°$ box (3° in declination $\times 8.4°$ in right ascension), which should contain 71% of the signal. The estimate of background is obtained by averaging over showers in a strip of declination $\pm 1.5°$ centered on $-69°$, excluding the box centered on SN 1987A. Averaging over 40 off-source bins, we find $B = 2346$, with an rms fluctuation of $54 \pm 6$. The 95%-C.L. upper limit is therefore $1.64\sqrt{B} = 79$ for the total signal from the direction of SN 1987A during the 449 h for which we have data. The observed number in the bin centered on the supernova is 2292. We can therefore set a 95%-C.L. limit on a signal at 100 TeV (averaged over the observing times in Table I) of

$$\frac{dI}{d\ln E} < \frac{79}{(7690\ \mathrm{m}^2)\times(449\ \mathrm{h})\times 0.71} \approx 0.9\times 10^{-12}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}. \quad (1)$$

The main result of the paper is Eq. (1). The limit is a conservative one because the source bin has fewer counts than the average background. To make a comparison with the results reported by the other groups, we calculate the limit on power in accelerated protons at the source $L_p$ for the "standard" $\gamma = 2$ spectrum of Ref. 5. Table II summarizes the results of seven experiments.

The only signal reported so far is from the JANZOS air Cherenkov experiment,[15] which reports a flux of photons on 14–15 January 1988 of

$$F_\gamma(>3\ \mathrm{TeV}) \sim 2\times 10^{-11}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

at the $3.9\sigma$ level. In terms of the standard model of Ref. 5 this would correspond to $L_p \sim 2\times 10^{39}$ ergs/s for these two days. It is interesting to note that 14–15 January was during a time of increasing x-ray luminosity (particularly for soft x rays),[18] that peaked around day 332. Although SPASE was off on 14–15 January (see Table I), the epoch of high x-ray activity spans the period for which we report data here. According to one model,[19] intense, soft-x-ray emission could be associated with pulsar activity and possibly with particle acceleration.[20]

If photon production is continuous at the level corresponding to $L_p \sim 10^{39}$ ergs/s (a level we believe does not

TABLE II. Limits on air showers from SN 1987A.

| Experiment | Date, exposure | Energy (TeV) | $L_p$ (ergs/s) |
|---|---|---|---|
| Ciampa *et al.* (Ref. 12) | 23 Feb.–30 Aug. 1987<br>185 days | $\geq 200$ | $< 10^{41}$ |
| Raubenheimer *et al.* (Ref. 13) | 20–21, 25–26 Nov. 1987<br>3 h | $\geq 1$ | $< 10^{39}$ [a] |
| Bond *et al.* (Ref. 14) | 13 Oct.–3 Dec. 1987<br>34.6 days | $> 100$ | $< 5\times 10^{39}$ |
| Bond *et al.* (Ref. 15) | Dec. 1987–Jan. 1988<br>42 h | $\sim 3$ (median) | $< 5\times 10^{38}$ |
| Morello (Ref. 16) | 22 Aug. 1987–27 Mar. 1988<br>71 days | $> 100$ | $< 10^{41}$ |
| Chadwick *et al.* (Ref. 17) | | $> 0.4$ | $< 2\times 10^{39}$ [b] |
| This paper | See Table I<br>18 of 42 days | $> 50$<br>$E_{\mathrm{median}} \sim 100$ | $< 3\times 10^{39}$ |

[a]We note that Chadwick *et al.* (Ref. 17) have questioned this flux limit, which was derived from 3 h of observation, but we are not in a position to elucidate the question.

[b]This limit is our interpretation of their quoted ($3\sigma$) flux limit of $1.6\times 10^{-10}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.

interfere with the successful explanation of the optical light curve due to radioactivity[21]), then $\sim$100-TeV photons should eventually be detectable with air-shower experiments—provided the parent spectrum extends sufficiently above 100 TeV. (The ultimate sensitivity of SPASE is significantly better than required for $10^{39}$ ergs/s.) If the photon production is sporadic, or if the accelerator itself is sporadic, then individual outbursts would need to be more powerful to be detected by air-shower experiments—even if the spectrum extends to ultrahigh energies. This is because, with presently available areas, an air-shower experiment requires long observing times to obtain a sensitivity comparable to that of an atmospheric Cherenkov experiment, which operates at lower energies and higher fluxes. In any case it is clear that both kinds of measurement are highly desirable to obtain the maximum information about SN 1987A or other possible sources of TeV and PeV particles.

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