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UPPER LIMIT FOR ULTRA-HIGH-ENERGY GAMMA RAYS FROM SN 1987A OBTAINED BY ČERENKOV TECHNIQUE AT LARGE ZENITH ANGLES

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ABSTRACT

The supernova SN 1987A has been observed with the JANZOS cosmic-ray facility at the Black Birch Range in New Zealand since 1987 October. From 1988 May to July, observations were carried out using the Čerenkov telescope at a zenith angle of 68°. By working at large zenith angles, the effective detection area and energy threshold are both increased. From 39 hr of observation, an upper bound of 5.7×10^{-14} cm^{-2} s^{-1} on the flux of gamma rays with energies ≥ 75 TeV is obtained at the 95% confidence level. This flux limit corresponds to the gamma ray luminosity of 10^{37} ergs s^{-1}.

Subject headings: gamma rays: general — stars: supernovae

I. INTRODUCTION

The supernova SN 1987A in the Large Magellanic Cloud provides a unique opportunity for various studies. A rapidly rotating magnetic neutron star may accelerate particles to high energies, and these may interact with supernova ejecta to produce high-energy gamma rays (Sato 1977; Berenzinski and Prilutsky 1978; Shapiro and Silberberg 1979; Gaisser, Harding, and Stanev 1987; Berenzinski and Ginzburg 1987; Yamada *et al.* 1988). High-energy particles may also be generated by a shock mechanism when supernova ejecta collide with circumstellar clouds (Honda, Sato, and Terasawa 1989). Measurements of high-energy gamma rays produced by SN 1987A are thus used to deduce properties of a young supernova remnant and a newly born neutron star.

The JANZOS cosmic-ray facility at Black Birch in New Zealand has been used to monitor the flux of high-energy gamma rays produced by SN 1987A since 1987 October (Bond *et al.* 1988*a*, *b*). Observations made with a scintillation detector array from 1987 October to December yielded an upper limit on the steady flux of gamma rays with energies ≥ 100 TeV of 1.1×10^{-12} cm^{-2} s^{-1} at the 95% confidence level, and observations made with a Čerenkov telescope in 1987 December and 1988 January yielded an upper limit on the steady flux of gamma rays with energies ≥ 3 TeV of 6.1×10^{-12} cm^{-2} s^{-1}. Evidence for the detection of a burst of gamma rays with energies ≥ 3 TeV was obtained on 1988 January 14 and 15 at a time when the *Ginga* satellite (Tanaka 1988) recorded a maximum of X-ray emission.

In this *Letter*, results obtained using the Čerenkov telescope between 1988 May and July are reported. For these observations, the zenith angle of the supernova was large, and this resulted in both the effective detection area of the telescope and its energy threshold being increased. As a consequence, a significant upper bound on the gamma-ray flux was obtained.

II. EXPERIMENTS

The JANZOS Čerenkov Telescope consists of three mirrors of 2 m diameter and 2 m focal length, each arranged at the vertex of an 80 m triangle. The elevation angles of the mirrors are variable, but their azimuths are fixed at the meridian and they record meridian passages of objects only. Ten fast 2″ phototubes (Hamamatsu H1531) with high-gain GaAs first dynodes are arranged at the focal plane of each mirror and view a strip of sky along the path of an object. Each phototube sees an area of sky 2°.3 × 2°.3, and their outputs are fed into analog-to-digital (ADC) and time-to-digital converters (TDC). The ADC and TDC information is used to determine the energies and arrival directions of gamma rays and cosmic rays, respectively, as described previously (Bond *et al.* 1988*b*). The angular resolution is estimated by simulations (Gibson *et al.* 1982; Gupta *et al.* 1982) to be about 0°.5 (FWHM). In order to compensate for the effect of variable background illumination caused by stars, a servocontrolled system of light-emitting diodes was used to keep the DC currents of the phototubes at the constant value used previously (i.e., ~40 μA; Bond *et al.* 1988*b*).

We can observe SN 1987A during two 3 month periods each year. In November–January it crosses the meridian nightly at a

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zenith angle of approximately 28°, and in May–July it crosses nightly at zenith angle of approximately 68°. In 1988 May–July we observed SN 1987A for 39 hr, and ~50,000 events were recorded around the SN 1987A region ($\Delta\alpha \sim 50^\circ$. $\Delta\delta \sim 3^\circ$).

As indicated by Sommers and Elbert (1987), Čerenkov observations at large zenith angles enjoy the advantage of a very large detection area. Inclined showers with large zenith angles require the Čerenkov light produced in the upper atmosphere to travel a relatively large distance, and the angular spread of the Čerenkov light (~1°) produces a relatively large light pool. However, it is inevitable that the light intensity is reduced and the energy threshold of the telescope is increased.

III. RESULTS

The method of analysis used here is the same as that used previously (Bond *et al.* 1988*b*). The directional response of the telescope is determined from the observed angular distribution of events, $f_1(\phi)$, where ϕ denotes hour angle. The response of the telescope may also vary with time because of changing sky conditions. This is monitored by the trigger rate, $f_2(t)$. The product $f_1(\phi) \times f_2(t)$ determines the expected detection efficiency at ϕ and time t. The integral of the product $f_1 \times f_2$ at a constant value of right ascension yields the expected number of background cosmic rays as a function of right ascension.

The ratio of observed-to-expected event numbers in each right ascension bin is examined to search for any excess over the cosmic-ray background. In Figure 1 the histogram shows the distribution of observed events in the declination strip $-69\overset{\circ}{.}3 \pm 0\overset{\circ}{.}5$ as a function of right ascension. The smooth curve indicates the expected number of events as defined above. There exists no significant excess at the position of SN 1987A (84° in right ascension). The observed and expected numbers of events in a $4\overset{\circ}{.}5$ right ascension bin centered on the SN 1987A direction are 1213 and 1232.9, respectively. Using the same statistical analysis as that described previously (Bond *et al.* 1988*b*), we obtain an upper limit of 58 for the number of gamma rays with 95% confidence.

In order to deduce an upper bound on the gamma-ray flux, we estimated the effective detection area of the telescope and the median energy of detectable gamma-ray showers. The angular distribution of Čerenkov light depends not only on the Čerenkov angle in air but also on the effect of multiple scattering of shower particles. The angular spread of Čerenkov light (half-angle) may be assumed to be roughly 1°, and the lateral distribution of photons may be assumed to be flat following the simulation of Hillas and Patterson (1987). The effective area and the median energy of detectable showers were calculated as a function of zenith angle following the approximation of Sommers and Elbert, but including the effect of the attenuation of Čerenkov light in the atmosphere. The depth of the maximum development of showers initiated by gamma rays was taken to be $X_m \sim 36$ g cm^{-2} ln$(E/74$ MeV) (Greisen 1956). It was assumed that the absorption of Čerenkov light is caused mainly by Rayleigh scattering for which the mean free path in air is 2974 g cm^{-2}. The photometric extinction coefficients for blue light and UV light at Black Birch are ~0.3 and ~0.5 mag per atmosphere, respectively (Forbes 1989). Figure 2 shows the calculated values of the effective area and the median energy of detectable gamma rays as a function of sec θ, where θ is the zenith angle. Since the average zenith angle is 68° in our case, the path length of the Čerenkov light from shower maximum to observation point is about 27 km. The effective area and the median energy for primary gamma rays are given as 7.2×10^9 cm^2 and 75 TeV, respectively, in good agreement with the detailed calculations of Sommers and Elbert.

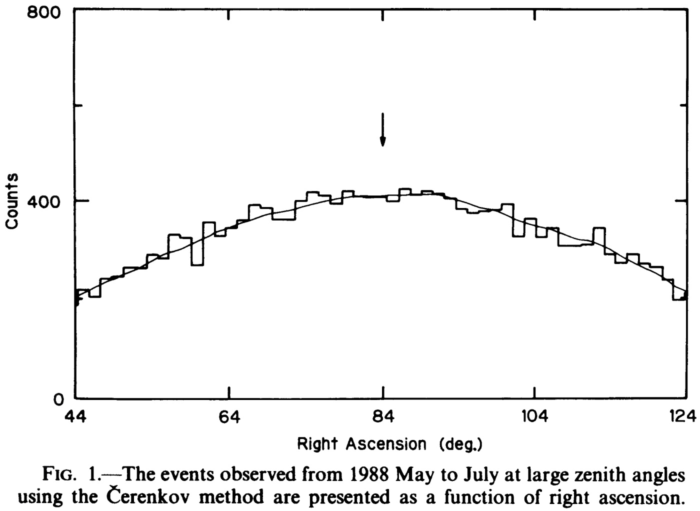

FIG. 1.—The events observed from 1988 May to July at large zenith angles using the Čerenkov method are presented as a function of right ascension. Only events in the declination strip $-69\overset{\circ}{.}3 \pm 0\overset{\circ}{.}5$ are included. The bin width is $1\overset{\circ}{.}5$ in RA. The smooth curve indicates the expected one. There is no significant excess around SN 1987A (right ascension 84°). The median energy of detectable showers is 75 TeV.

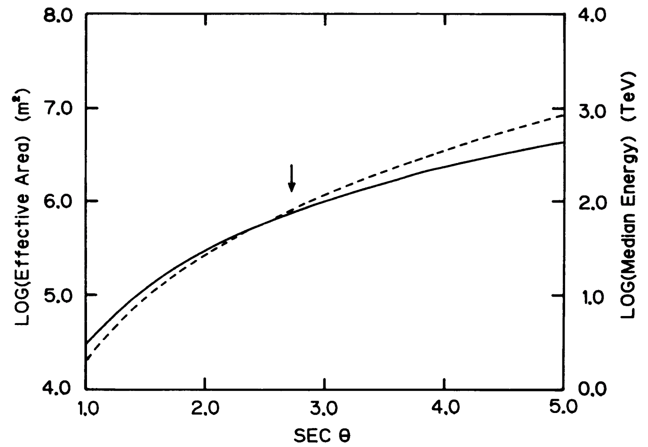

FIG. 2.—The effective area and the median energy of detectable showers for various zenith angles are shown by solid line and broken line, respectively. They are estimated by the method of Sommers and Elbert (1987). The effective area and the median energy in the present experiment are estimated to be 7.2×10^5 m^2 and 75 TeV, respectively.

IV. CONCLUSIONS

There is no significant excess in the right ascension distribution in the observations from 1988 May to July at large zenith angles, and we obtain an upper bound on the gamma-ray flux from SN 1987A of 5.7×10^{-14} cm^{-2} s^{-1} for energies greater than 75 TeV at the 95% confidence level. By assuming a power-law energy spectrum with a differential index of 2.0 and a cutoff at 10^{17} eV, an upper bound for the gamma-ray luminosity of approximately 10^{37} ergs s^{-1} is obtained.

In Figure 3 this result (designated by "J5") is shown in comparison with several other results. The uncertainty in the estimation of the median energy and the effective area changes the upper limit of the flux along the slanting bar in the figure. "J2" and "J3" are the previous TeV results (Bond *et al.* 1988*b*), corresponding to the upper limit for DC signals obtained by the observations during 1987 December and 1988

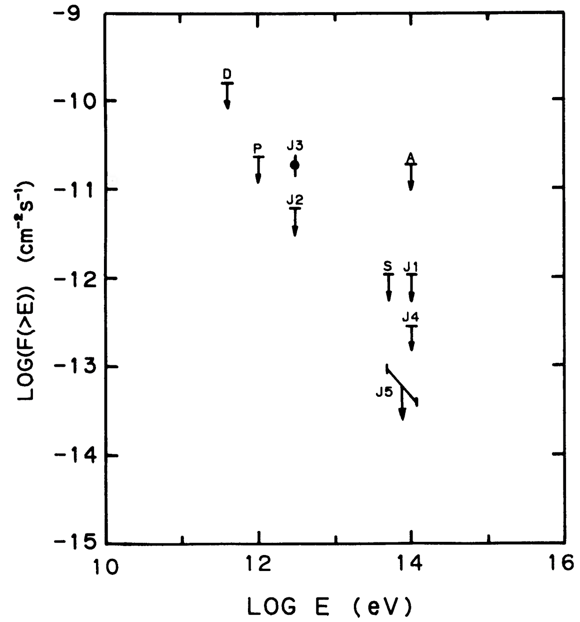

FIG. 3.—The present result designated by "J5" is shown in comparison with several other results. The uncertainty in the estimation of the median energy and the effective area changes the upper limit of the flux along the slanting bar. "J2" and "J3" are our previous TeV results obtained by the observations during 1987 December and 1988 January. The 100 TeV result obtained by the JANZOS scintillation detector array is indicated by "J1." "J4" represents an updated result. Other observations are shown by "A" (Ciampa *et al.* 1988), "P" (Raubenheimer *et al.* 1988), "D" (Chadwick *et al.* 1988), and "S" (Gaisser *et al.* 1989).

January and the burst of 1988 January 14–15, respectively. The result obtained by the JANZOS scintillation detector array (Bond *et al.* 1988*a*) is indicated by "J1" and an updated result obtained with this detector is indicated by "J4" (flux limit of 4.0×10^{-13} cm^{-2} s^{-1} at the 95% confidence level obtained from the observations during 1987 December 13 and 1989 January 9, 13 months). Other results are shown as "A" (Adelaide group, Ciampa *et al.* 1988; period approximately 1987 February to August, 185 days), "P" (Potchefstroom, Raubenheimer *et al.* 1988; 1987 November, 3 hr), "D" (3 σ upper limit obtained by Durham group, Chadwick *et al.* 1988; approximately 1988 January to February, 36 hr; they carried out several other observations of SN 1987A), and "S" (SPASE, Gaisser *et al.* 1989; approximately 1988 January to February, 449 hr). The present work places the most restrictive upper bound on the flux of high-energy gamma rays from SN 1987A.

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