A fast optical Cerenkov system for directional studies of possible gamma-ray sources[1]

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The system observes pulses of light from the night sky, produced by small showers in the atmosphere. It uses two 90-cm $f/0.5$ mirrors in coincidence and with effective full field of view about 1°; but unlike previous systems of this kind it has a reduced integration time of about 3 ns and coincidence resolving time of 5 ns, the object being the selection of the fast collimated light cone originating from the high-energy early generations of the shower above 10 km rather than the slower, less directed, but more intense component from the vicinity of the maximum. The threshold energy for γ-ray showers is difficult to determine from the observed counting rate for proton showers, since the early development of the showers is different, but is believed to be in the vicinity of 10^{12} eV. Preliminary drift scans have been carried out in the winter of 1966–67 at a site 300 m above sea level near Dublin. Several drift scans have been carried out on the Crab nebula, 3C196, and 3C286; and individual runs on some other objects including a possible source of neutral primaries at about 1100+20 reported by Hesse *et al.* The Crab nebula results show an apparent positive effect which, if it is real, would correspond to a flux of about 10^{-10} photons/cm^2 s, but the results are difficult to assess because of poor atmospheric conditions. Some other apparent positive effects have been observed, but none are significant statistically.

1. INTRODUCTION

The observation of Cerenkov pulses from the night sky has been used in a number of experiments to establish flux limits for γ rays or other neutral primaries, from possible cosmic sources in the energy region 5×10^{12} to 10^{14} eV (Galbraith and Jelley 1955; Chudakov *et al.* 1963; Long *et al.* 1966). Some small apparent positive effects have been found, notably from Cygnus A and from the quasar 3C147, but none of these have had high statistical significance.

In the case of the Crab nebula, from the flux limits set, it has been possible to rule out a direct nuclear origin for the high-energy electrons. Calculations of the γ-ray intensities produced by inverse Compton reactions of the electrons with low-energy photons (Gould 1965) predict somewhat lower fluxes than the experimental limits. Recently, however, Appa Rao (1966) has shown that if inverse Compton interactions of the electrons with the universal microwave flux are taken into account, the expected flux of γ rays in the region 10^{12}–10^{13} eV is greater than the limits set experimentally by Chudakov *et al.* or by Long *et al.* It would appear, therefore, that electrons of energy greater than about 10^{14} eV are rare in the nebula. The Cerenkov technique affords a more direct test of both of these theoretical models than is possible with current satellite or rocket-borne detectors at lower energies.

More significant results on most likely sources would be obtained if the angular resolution of Cerenkov systems could be improved and the energy thresholds reduced below 10^{12} eV. The angular resolution has in the past been limited by coulomb scattering of the electrons, at or beyond the maximum, where most of the observed light originates, and angular fields of view and resolution times have been chosen to allow for this scattering and to obtain a maximum counting rate for showers. Typically, resolutions of about 3° and threshold energies of about 5×10^{12} eV have been obtained for proton-induced showers with counting rates of 100

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showers per min or more. The duration of the light pulse is dependent on the optical field of view, and at 3–5° the integration time required to give the highest counting rate is about 20 ns.

The high-energy particles in the early generations of the cascade, which for a photon-induced shower occur above 10 km, will produce a faster and more directed pulse of light. Cascade electrons with energies higher than about 10^{10} eV will be essentially unscattered, and will deposit their Cerenkov light in a narrow annulus 100–130 m in radius at sea level, with a time spread of only about 3 ns. Lower-energy particles in the early generations broaden this annulus both laterally and in time, but for photon-induced showers a significant fast component is expected. In proton-induced showers the fast component is expected to be less intense and less directed, because the primary energy is released into the electron component over a greater track length.

2. EXPERIMENTAL SYSTEM

The system described here is optically similar to that used previously (Long *et al.*), but with an effective field of view 1° in diameter. Two mirrors, each 90 cm in diameter at *f*/0.5, are fixed with their axes parallel on a steerable altazimuth mounting, and viewed with fast photomultipliers at the foci. Signals from the individual photomultipliers are amplified, with an integration time of about 3 ns, and operate tunnel diode discriminators. One discriminator output is led direct to a fast coincidence unit. The other is switched, alternately through a coaxial switch, to direct and delayed lines before reaching the coincidence unit. The switching cycle is 3 s long, and the coincidence output is recorded by synchronously gated scalers, so that one scaler records genuine plus random coincidences and the other random coincidences only. A record of the random coincidences is therefore obtained throughout observation, and they can be subtracted to obtain the genuine coincidence rate. The d-c. current from the photomultipliers is recorded continuously and used to control servo circuits which drive small tungsten lamps at the center of each mirror. These are set to add an additional 20–30% to the background light from the sky, so that the total light observed by each photomultiplier is maintained constant, even with the passage of bright stars through the field of view.

The setting accuracy of the mounting is better than 0.2°; drift-scan observations are carried out by setting on a point through which the source will pass, and observing the counting rate throughout the transit. Since the fast light component falls in a cone of radius 0.6–0.8°, a source of γ rays will produce two peaks in counting rate 3–6 min before and after transit. The times at which the peaks occur relative to transit depend somewhat on the declination of the source, and their width on the details of shower development, as well as integration time, field of view, and optical aberrations. In the present system, severe coma occurs off-axis, but using theoretical calculations of shower development by Rieke (1966, private communication), a double peak would be expected for an equatorial source, provided the setting accuracy is better than about 0.3°.

3. PRELIMINARY RESULTS

The system is located at a dark site 300 m above sea level near Dublin. Preliminary observations have been made during the winter of 1966–67. With counting rates in the individual channels set at 1 000 to 5 000 counts per s, a shower counting rate of about 10 events per min and a prompt-to-random ratio of about 3 to 1 are obtained at the zenith. The counting rate with a 20-ns resolving time and 3° field of view was about 100 counts per minute; but since the fast cone of light is weaker for proton-induced showers than for γ-ray primaries, and the collection area in the fast system is only about 10^4 m^2, as against 10^5 m^2 for the slow wide-angle system, the threshold energy is believed to be lower in the present system. Detailed calculations are difficult because of the uncertainties in the development of the nuclear cascade, but a threshold energy of about 10^{12} eV for photon-induced showers is consistent with both the observed counting rate and the estimated absolute sensitivity of the system.

Several drift scans have been carried out on the Crab nebula, 3C196, and 3C286; and individual runs with low significance on

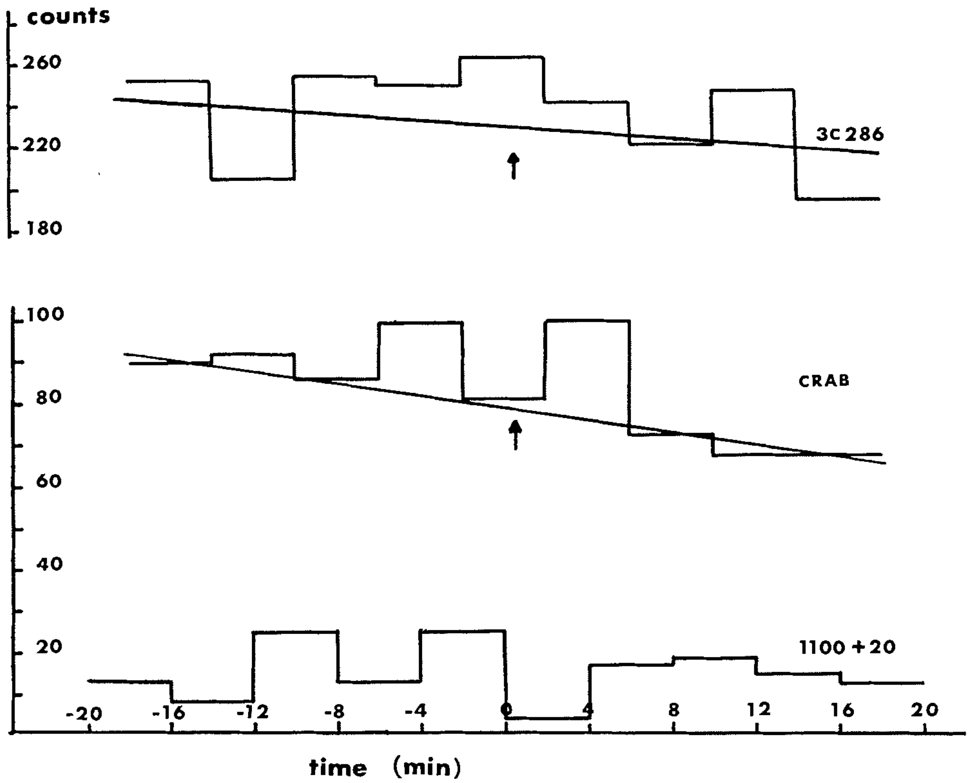

FIG. 1. Drift scans on 3C286, the Crab nebula, and the possible source 1100+20, averaged over 4-min intervals. For 1100+20, the zero of time represents a right ascension of 1100 h. In the other sources the exact time of transit is indicated by arrows.

3C147, 3C273, Cygnus A, the apparent source of neutral primaries at 1100+20 (Hesse *et al.* 1967), and the anomalous radio source 1607+26. The sum of nine drift scans on the Crab nebula and of eight scans on 3C286, with counts averaged over 4-min intervals, is shown in Fig. 1. Unfortunately there is a tendency for the counting rate to decrease with time, which occurred in most of the individual scans. We ascribe the effect to changes in atmospheric transparency, which seem to produce more marked variations in counting rate than in the previous slow system. If the apparent double peak in the Crab nebula runs were accepted as due to genuine γ rays, it would correspond to a flux of about 1.5×10^{-10} photons/cm^2 s, at an estimated threshold energy of about 2×10^{12} eV. This apparent flux is compared with the theoretical predictions and with other experimental points in Fig. 2. The apparent effect is statistically significant at about the 1% level, but atmospheric variations render this figure unreliable. The counting rate for the Crab nebula is rather low, and the threshold energy high, because of the rather large zenith angle of observation.

The drift scans on 3C286 are typical of most of the other observations. They are compatible with zero flux of γ rays, show fluctuations somewhat greater than would be expected from Poisson statistics, and being taken close to the zenith, correspond to an estimated threshold energy of about 10^{12} eV. One scan has been made in the vicinity of the apparent source found by Hesse *et al.*, at about RA 1100, δ +20. It showed an apparent double peak centered at 1054 +20, but it is not statistically significant. It is shown also in Fig. 1, centered at 1100 h.

Some preliminary observations have been made with a three-mirror system, having

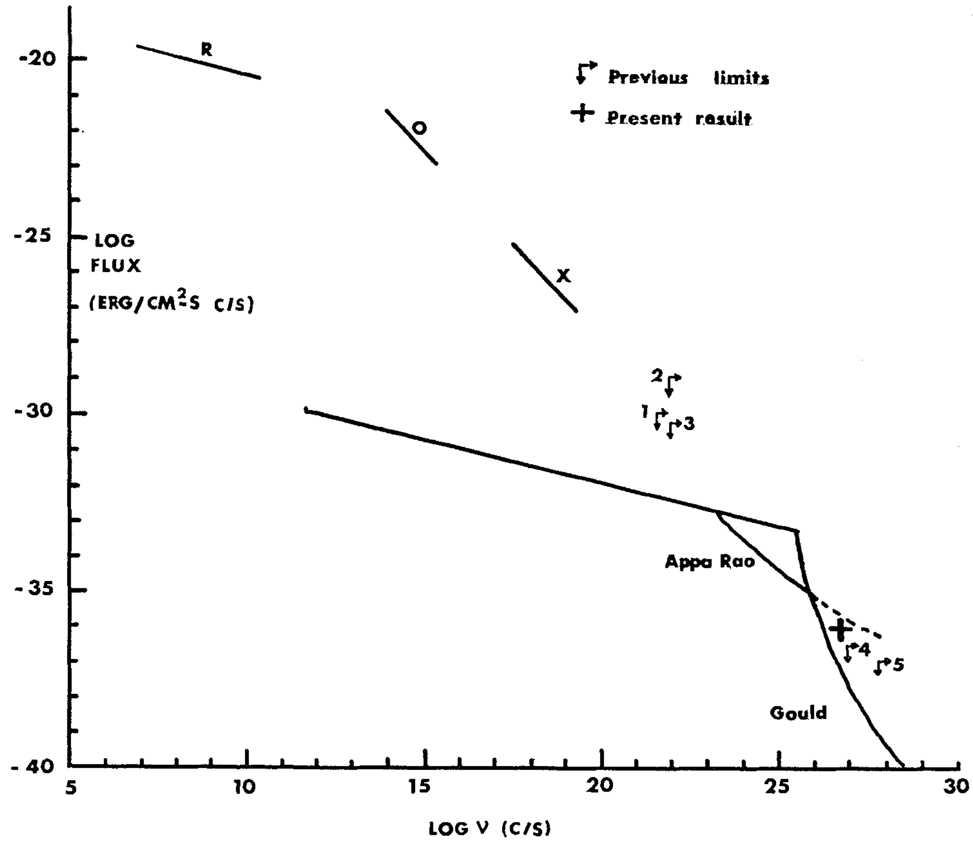

FIG. 2. Differential photon spectrum predicted by Gould and by Appa Rao, compared with experimental observations. Experimental upper limits: 1, Frye and Smith (1965); 2, Kraushaar *et al.* (1965); 3, Cobb *et al.* (1965); 4, Chudakov *et al.* (1963); 5, Long *et al.* (1966). The present observations are marked with a cross, which indicates approximately the uncertainties in energy and flux.

similar characteristics. It is intended to improve the optical characteristics of the system, and to continue observations.

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