VERY HIGH ENERGY GAMMA RAYS FROM THE CRAB PULSAR

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ABSTRACT

Observations of the Crab pulsar using the atmospheric Cerenkov technique were conducted for 22 hours on Sept.-Oct. 1984. The light curve obtained shows a single peak at approximately the position of the expected main peak with a significance level of 3.2σ. The pulsed flux above 200 GeV is $2.5 \pm 0.8 \times 10^{-11}$ cm^{-2}s^{-1}.

1. Introduction.

Observations of the Crab pulsar (PSR 0531+21) at energies above 100 GeV have been attempted for more than 15 years, with mixed results. Some authors have reported upper limits; others have reported values for a pulsed flux with, however, conflicting evidence in regard to the shape of the light curve. A recent and, in some respects, the most convincing case for a pulsed flux has been presented by the Durham Group (1). Their light curve for energies above 1,000 GeV shows a single, narrow peak at the position of the main peak seen at other wavelengths, at a significance level of better than 4σ.

In this paper we present the results of 22 hrs. of observation in 1982 of the Crab pulsar using the atmospheric Cerenkov technique. The light curve obtained shows a single peak at approximately the position of the expected main peak with a significance level of 3.2σ. The peak is substantially broader than observed by reference (1). This may be related to our somewhat lower threshold of energy of 200 GeV.

2. Observations.

The JPL solar energy mirrors at Edwards Air Force Base, California, a dry desert location at an elevation of 0.7 km and 35° N latitude were used for these observations (2). The two 11 m diameter, 6.6 m focal length mirrors were separated by 24 m approximately on a north-south line. The image of a point source was observed to be approximately 6-8 cm in diameter. The tracking of point sources by the mirrors was accurately calibrated and monitored each night by aligned television cameras, one on each mirror, which recorded the images of stars as faint as fourth magnitude.

These observations were carried out in a tracking mode (2). Two PM tubes were placed at the focus of each mirror offset from one another by 3° in azimuth and offset from the mirror's principal axis by 1.5°. One channel looked at the source region and the other at a background region. The role of signal and background channels were interchanged every hour.

The four pulse heights, four time differences and the universal time to the nearest 0.1 msec were recorded on magnetic tape via CAMAC electronics. Constant fraction discriminators were used to improve the time resolution. The dynamic range of the pulse height spectra was more than 100 for each of the PM tubes. Singles rates for each of the four PM tubes were also recorded on magnetic tape, along with coincidence rates of the source and background channels and delayed coincidences, effectively monitoring the accidentals. This information was useful in determining whether suspected transient phenomena were real or spurious.

This detector was used to observe Cygnus X-3 (3,4,5) and the Crab pulsar (6). The data for the Crab were obtained during September and October 1982. The total observation time was 16 days. Of these, one was over-cast, three were cloudy and on four only a single mirror was operational. From the remaining eight good days, 22 September was discarded as there was a 7 msec glitch in the atomic clock sometime during the day. Two of the data runs on 23 September were rejected due to a 0.4° discrepancy in the tracking of the source. This left six good days in October (12-16, 19 October 1982) and one run on 23 September for the analysis.

3. Data Analysis. Four cuts were applied to discriminate against background. The first required that corresponding PM tubes in each mirror have a signal above threshold. This established that only coincident data were analyzed. The second cut, at a pulse height corresponding to about 200 GeV, defined the lower energy threshold of the detector. The third cut of ±2ns was applied to the time difference between the pulses received by the two mirrors to eliminate accidental coincidences. This time difference corresponds to approximately ±3° variation in the direction of the incoming signal. The fourth cut exploited a significant difference between the proton and gamma induced Cerenkov radiation. The VHE gamma ray induced Cerenkov light distribution on the ground is approximately uniform over a diameter of more than 100 meters but the corresponding distribution for proton induced showers is more strongly varying with radial position on the ground. This difference has motivated a pulse height difference cut. The normalized difference in pulse height may be written as: (PH1-PH2)/(PH1+PH2), where PH1 and PH2 are the pulse heights in the corresponding PM tubes in the mirrors 1 and 2 respectively. A histogram of this function varied between -1 and +1 and showed a broad peak around zero. A cut of ±0.4 was applied around the peak so that events with approximately equal pulse height in both mirrors were selected and analyzed. The value of this cut parameter is not critical, however this cut does significantly improve the pulsed signal. Without this last cut the evidence for the pulsed flux would have been at approximately the 2σ level.

The time for each event has been converted from UTC to Barycenter Corrected Universal Time using the MIT solar system ephemeris (7). We have used an accurate radio ephemeris (8) to assign an absolute phase to each event. A phase diagram with bin positions chosen to allow comparison with the COS-B data (9) (Fig. 1a) appears in Figure 1.

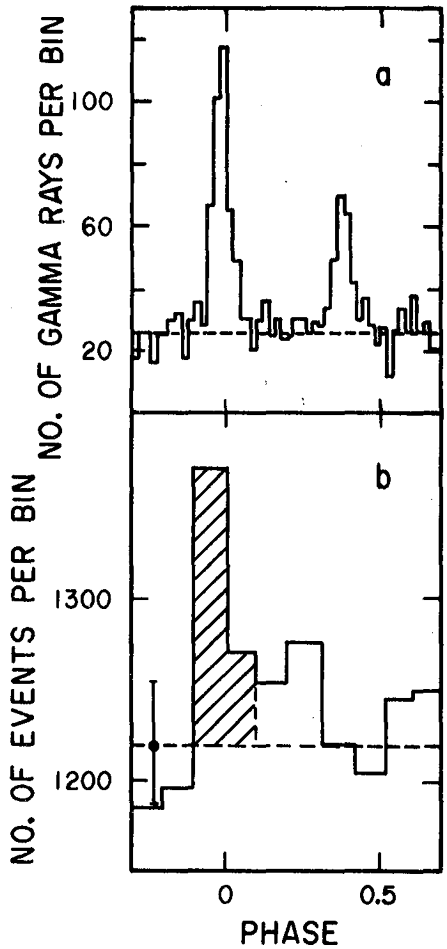

Fig. 1 (a) The average light curve for 100 MeV gamma rays emitted by PSR 0531+21 (9). (b) The light curve for coincident events recorded from PSR 0531+21 in September and October 1982. The background level calculated from phases 0.5 to 0.9.

3. Results. There are 12,466 coincidence events in the light curve. The expected number of events, for the two bins on either side of the expected main peak position based on the 4,876 events between phase 0.5 and 0.9 for which the COS-B data suggest no gamma ray emission, is 2,438. We see a total of 2,640 which is an excess of 202 at the position of the main pulse similar to the results of Dowthwaite et al. (1). The significance of the peak is about 3.2σ using the likelihood ratio method (10). There is no evidence for an interpulse, in agreement with (1). COS-B (9) reported an interpulse/main pulse ratio decreasing 1976 to 1981. The strength calculated by applying the convention used in (1), of the effect at the main pulse (2,640) is 1.7%±0.5%, about seven times stronger than their signal strength. There is some evidence that the strength of the pulsed emission was not constant during our observation. The main pulse is found to be broader than that reported in (1). This may be related to our lower threshold energy 200 GeV.

The results were checked to see whether the excess counts in the main pulse were concentrated in the source direction. Light curves were plotted for different arrival directions of the events with the same ±2 nsec time difference window. The ratio of the pulsed to background counts decreased rapidly when direction of acceptance varied beyond 1° from the true source direction. We have also performed an identical and simultaneous pulse analysis for the background channel, and no significant peaks were seen.

The total duration of observation was 7.99×10^4 seconds and the total effective area the detector sampled was approximately 10^8 cm^2. If we accept the pulsed component as the single main pulse, this excess constitutes a time-averaged pulsed flux of $(2.5\pm0.8)\times10^{-11}$ $cm^{-2}sec^{-1}$ above 200 GeV. The error quoted is purely statistical; systematic errors in the flux and energy threshold are estimated to be a factor of two. The energy spectrum of gamma rays from Crab pulsar (PSR 0531+21) over the range 1-10^4 GeV is shown in Figure 2. We include, in addition to the present result, values for the previously published fluxes, but not upper limits. This result with others in the energy spectrum confirms the existing view that the spectrum must steepen in the region between the balloon-borne gas Cerenkov detector results (below 10 GeV) and those from ground-based atmospheric Cerenkov experiments (above 100 GeV).

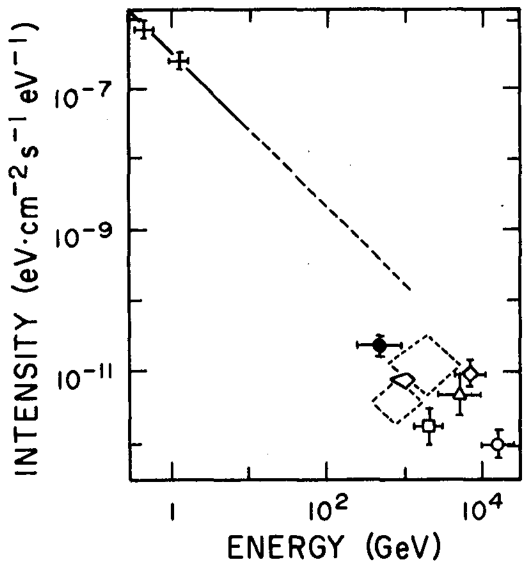

Fig. 2 The energy spectrum of gamma rays emitted by PSR 0531+21. Current data are shown as a filled circle; earlier results are shown as broken-lined squares (11); open square (12); triangle (13); open circle (14); diamond (15); crosses (16); heavy-lined trapezoid (1).

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