

OBSERVATIONS OF THE CRAB NEBULA AT ENERGIES $> 4.10^{11}$

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1. Introduction. Since the development of gamma-ray astronomical telescopes, the Crab Nebula has been a prime target for observations. From 100 to 1000 MeV, the pulsar PSR0531 is the dominant source with a light-curve similar to that seen at lower energies; there is also some evidence for longterm amplitude variations but none for emission from the Nebula itself. In the very high energy gamma-ray region there have been reported detections of pulsed emission with longterm time variations from minutes to months (Gibson et al. 1982; Bhat et al. 1984; Grindlay et al. 1975). Recently a pulsed flux has been reported that persisted over a long time interval (Dowthwaite et al. 1984). Fazio et al. (1972) reported the detection of a flux from the Nebula at the 3σ level at energies of 3×10^{11} eV; there was no evidence of periodic emissions on any time scale during the three years of observations. Mukanov (1983) has reported the detection of gamma rays at energies $> 2 \times 10^{12}$ eV at the 4.5σ level from the vicinity of the Crab Nebula; since fast timing was not employed, it was not possible to tell if any, or all, of this flux was pulsed.

Here we report a new measurement of very high energy gamma rays from the Crab Nebula using the imaging system on the Whipple Observatory 10m reflector.

2. Observations. All of the observations were made with the full 37 element camera. The camera and operating procedure have been described elsewhere (this conference, OG 9.5-4). Only data taken on clear nights were accepted for this analysis; atmospheric and system stability were checked by comparing the minute-by-minute counting rates in each run. The observations were taken during the dark periods of Nov-Dec 1983, Jan-Feb, Oct-Nov 1984 and Jan-Feb 1985.

3. Results. In its simplest interpretation, the imaging detector can be considered as a single channel atmospheric Cherenkov detector and used to compare the total number of events ON and OFF the source. The total number of ON events was 329,169 and OFF was 328,236; the difference +933 (or 1.1σ where $\sigma = \sqrt{\text{ON} + \text{OFF}}$) is not significant. Future analysis will make fuller use of the imaging properties of the

detector but the analysis presented here uses a very simple imaging algorithm. To eliminate events close to the detector threshold (particularly in the 1983/4 observing season when the trigger was any one tube of the inner seven) only those events whose total measured signal (all tubes) was > 90 photoelectrons were considered. Because the early simulations had indicated that gamma-ray showers might be smaller in angular extent than the measured background proton shower images, a selection was made based on the fraction of the light contained in the two highest pixels $r = (p_1+p_2)/\text{total}$. With $r > 0.75$, this selection rejects 99% of the events at the zenith and 97% at a zenith angle of 45° (figure 1(a)). The distribution of events with r is shown in figure 1(b).

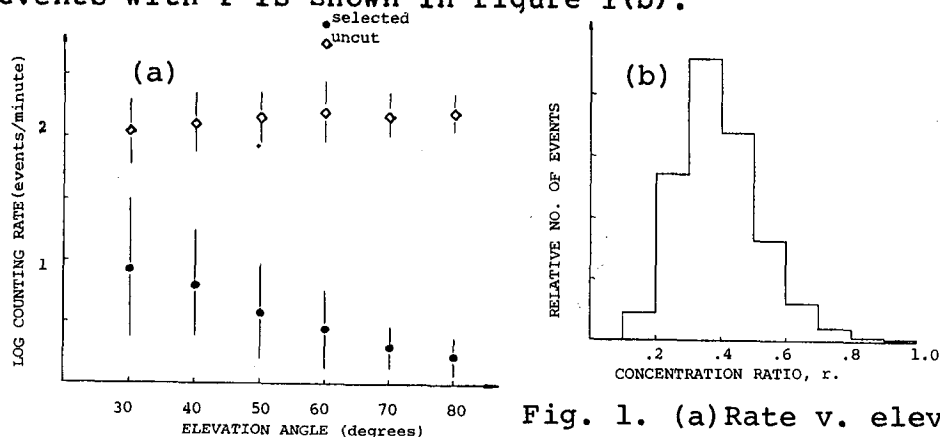


Fig. 1. (a) Rate v. elev.
(b) distribution of r .

When applied to all the above data, this selection corresponds to 8415 ON, 7709 OFF for a difference of $+708$ or $+5.6\sigma$. This is one of the most statistically significant detections of gamma rays at energies accessible to ground-based detection techniques from any source. Its interpretation is considered below.

To determine the optimum value of r , Table 1 shows how the signal level varies as a function of r and shower size. As these data represent a mixture of somewhat different operating conditions (in particular different triggering criteria), some caution must be exercised in interpreting Table 1. It is apparent however that, for this data sample, the choice of $r > 0.75$, size > 90 p.e. was close to optimum and this value has been used in the analysis of data from other sources (OG 2.2-9, 2.7-3, 2.1-11, and 2.4-4).

Table 1

Size > 90 p.e.	$r > 0.65$	$r > 0.75$	$r > 0.85$
1983/4 1/7	$+4.43\sigma$	$+5.24\sigma$	$+4.48\sigma$
1984/5 2/19	$+4.16\sigma$	$+3.48\sigma$	$+4.06\sigma$
Size > 150 p.e.			
1983/4 1/7	$+3.25\sigma$	$+3.89\sigma$	$+3.07\sigma$
1984/5 2/19	$+3.56\sigma$	$+1.66\sigma$	$+1.73\sigma$

We have also examined the selected data for evidence of monthly time variations such as those reported by Fazio et al. (1972). Our results are consistent with a steady flux during the period of the observations; there were no reported pulse glitches during this time.

4. Periodicity Analysis. The angular resolution of the technique is such that we cannot differentiate between gamma rays coming from the pulsar and the nebula on position alone. A signal from the pulsar can be identified on the basis of its characteristic time signature. To link observations in phase requires a well-determined pulsar ephemeris; this was available for the 1983/4 observation from radio observations at Jodrell Bank (A. Lyne, private communication). A phase analysis of the 1983/4 data shows no evidence for pulsed emission in either the unselected (raw) or selected data and indicates that less than 10% of the observed flux is pulsed; hence the observed flux must be associated with steady emission from the nebula. The complete timing analysis has not yet been undertaken but it should be possible to achieve a sensitivity similar to Dowthwaite et al. (1984).

5. Discussion. Assuming a collection area of $1 \times 10^4 \text{ m}^2$ for selected events, the observed effect is 708 events in 2032 minutes of observations giving a flux of 6×10^{-11} photons/cm²-s. The energy threshold is 400 GeV. Because of uncertainties in the simulations, a factor of 2 uncertainty in both energy and flux should be assumed. An upper limit to the pulsed flux based on the 1983/4 data only is $<1.1 \times 10^{-11}$ photons/cm²-s.

In figure 2 the predicted gamma ray energy spectrum from the Crab Nebula is plotted assuming an average magnetic field of 6×10^{-4} gauss (Gould (1965); Rieke and Weekes (1969)). A more rigorous calculation, which uses a radial model of the field, is also shown (Grindlay and Hoffman, 1971). This value agrees with the measurement of Fazio et al. (1972) but is in disagreement with the measurement of Mukanov (1983). The upper limit to the pulsar flux is not in conflict with the measurements of Dowthwaite et al. (1984).

6. Acknowledgement. This work is supported by the U.S. Department of Energy, the Smithsonian Scholarly Studies Fund and the National Board of Science and Technology of Ireland. We acknowledge the assistance of Kevin Harris in making observations.

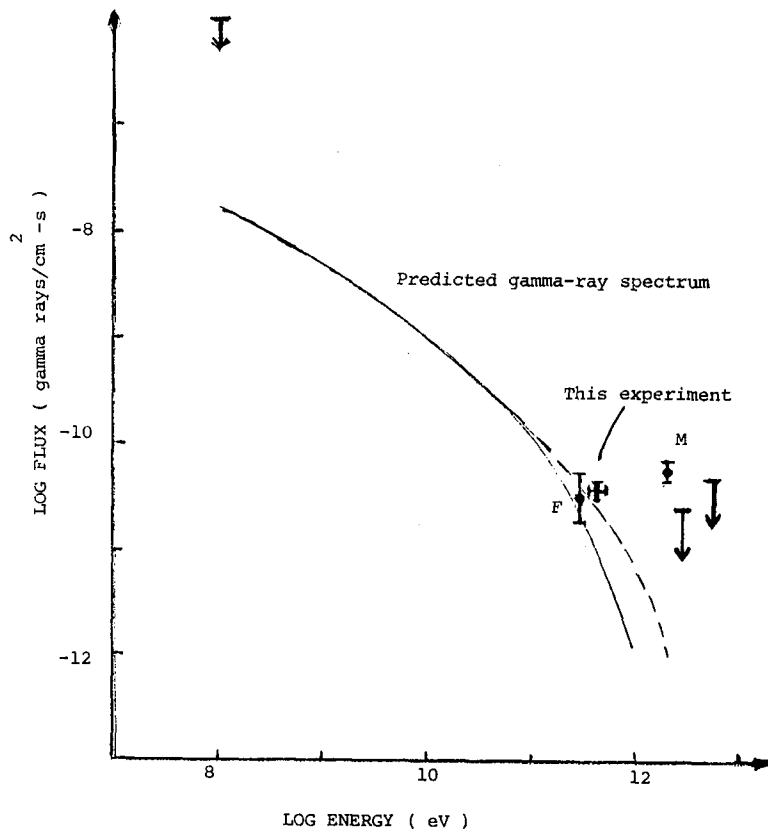


Figure 2. Gamma-ray spectrum from Crab Nebula. F=Fazio et al. (1972); M=Mukanov (1983). Unmarked limits referenced in Mukanov(1983). Solid line from Grindlay and Hoffman.1971, $B=6.10^{-4}$; dotted line-- from X-raysynchrotron electrons.

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