THE ASTROPHYSICAL JOURNAL, 209:592–601, 1976 October 15

EVIDENCE FOR A VARIABLE FLUX OF $>10^{11}$ eV GAMMA RAYS FROM NP 0532

J. E. GRINDLAY, H. F. HELMKEN, AND T. C. WEEKES
Center for Astrophysics, Harvard College Observatory and Smithsonian Astrophysical Observatory
Received 1976 February 2

ABSTRACT

The final analysis of observations of NP 0532 for pulsed high-energy γ-ray emission over the period 1969–1974 are reported. All the observations were made using the atmospheric Cerenkov technique in various operating modes. The results are consistent with the existence of a periodic γ-ray flux at energies greater than 8×10^{11} eV which is variable in phase and amplitude on a time scale of months.

Subject headings: gamma rays: general — nebulae: Crab Nebula — pulsars

I. INTRODUCTION

The pulsar in the Crab Nebula continues to be one of the most interesting objects for astrophysical study as well as the proving ground for pulsar theories. Recent observations of NP 0532 suggest that pulsars may not be regarded as "standard candles" or constant in many of their observable properties, especially at high energies. The early observations of period glitches of the Vela and Crab pulsars were the first indication of major variability on time scales of weeks. Associated with at least one glitch of NP 0532 have been changes in the wisp structure of the Crab (Scargle and Pacini 1971) and the pulsar dispersion measure (Rankin and Counselman 1973). There is some evidence that the major glitches were also accompanied by high-energy γ-ray emission (Fazio *et al.* 1972) which, given the later results we shall describe, could have been pulsed with variable phase. The observations of these glitches were perhaps the first to suggest that, despite the very high magnetic fields, pulsar magnetospheres are subject to certain instabilities such that plasma can be suddenly released.

More recent evidence for magnetosphere changes, or at least long-term changes in the radio emission region, is contained in the report of the smooth decrease in the (broad-band) radio pulsed flux from NP 0532 (Rankin, Payne, and Campbell 1974) and the associated changes in radio pulse shape (Lyne and Thorne 1975). At X-ray energies, there is also variability in a component (presumably NP 0532) of the Crab flux (Forman *et al.* 1974), at least one new pulse component (possibly related) in the X-ray light curve that is detectable on a time scale of minutes (Ryckman *et al.* 1975), and evidence for a substructure at the phase position of the optical interpulse (Helmken 1975).

We report here the final analysis of 5 years of observations of NP 0532 at very high ($>10^{11}$ eV) γ-ray energies that are consistent with a new and variable pulsed component. Although suggested previously (Grindlay *et al.* 1973; Helmken, Grindlay, and Weekes 1975), this component is "new" in the sense that it is not (apparently) an extrapolation from the X-ray and low-energy γ-ray spectrum and is variable in phase and intensity.

II. OBSERVATIONS

The observations reported here all employed versions of the atmospheric Cerenkov technique (Jelley 1958) whereby the optical Cerenkov light produced by relativistic electrons and muons in extensive air showers (EAS) initiated by a primary cosmic or γ-ray is detected by simple light receivers. All our observations were made at the 2.3 km level of Mt. Hopkins in southern Arizona and employed a 10 m reflector on an alt-azimuth mount (Rieke 1969) and a number of 1.5 m reflectors. Although the atmospheric Cerenkov technique provides large collection areas ($>10^8$ cm^2) and high angular resolution (0.5°–2°) the observations of γ-rays are made in the presence of a high background ($>99\%$ of detected rate) of cosmic-ray-initiated air showers. To detect discrete sources of γ-rays, a directional anisotropy in the air shower arrival distribution is sought in the vicinity of the suspected source. For a periodic source, greater sensitivity can be achieved by periodic analysis of the data from a continuously monitored suspected source direction. To achieve the maximum signal/noise ratio, we have employed a variety of operating modes to observe NP 0532. Since no strong γ-ray source has yet been detected which would permit the optimization of the detection techniques, the relative merits of the various modes of operation can only be estimated based on computer calculations of the Cerenkov light distributions and the experimentally determined light-detector sensitivities. We have emphasized operating modes that include partial cosmic-ray rejection, since these have yielded the most significant results.

Because of its large collection area, the 10 m reflector has an energy threshold of 10^{11} eV, a factor of 10 lower than the light-detector systems normally employed. The detection modes used to observe NP 0532 fall naturally into two categories: (1) single reflector modes which used the 10 m reflector only and (2) multiple reflector modes which used one or more

1.5 m reflectors in conjunction with the 10 m reflector. Except where noted, the 10 m reflector tracked NP 0532, thus yielding the optimum response for on-axis γ-ray-initiated air showers. Each mode will be described briefly below.

a) *Single Reflector*

i) *Single Beam*

The simplest Cerenkov detector consists of a single phototube at the focus of a mirror. With a 12.5 cm RCA 4522 at the focus, the 10 m reflector has a field of view of 1° (full field). On the basis of Rieke's light distribution calculation (Rieke 1969), this mode has the lowest γ-ray energy detection threshold. At the zenith for a dark sky, Rieke estimated that this configuration had an effective energy threshold of 90 GeV and a collection area of 1.3×10^8 cm^2; these values have recently been modified to those shown in Table 1 (Weekes 1976). This mode was used over the period 1969–1972 in the course of an experiment to search for a directional anisotropy in the air showers from the Crab Nebula. The shower rate was 200–300 per min; the time of arrival of each shower was recorded to 1 ms.

ii) *Multiple Beams*

In the event that the shower light distribution is in fact somewhat broader than Rieke had calculated (Porter 1973), the configuration shown in Figure 1*b* was used. Three 12.5 cm tubes were located 0.7° from the optical axis which was directed at the source. Two types of events were registered and identified. Type *A* were those in which either one or two of the tubes detected a pulse above threshold. For type *B* events, all three tubes had to be triggered. The sum of the amplitudes of the three tubes was recorded (5 bits) so that some crude pulse-height (and hence energy) information was available. Because of the coincidence requirement, the tubes could be operated at a factor of 2 lower threshold for type *B*. The time of arrival of each shower was recorded to 0.1 ms.

Observations with this mode were made in 1973 October–November and 1974 January.

iii) *Guard Ring Configuration*

Seven tubes were mounted, as shown in Figure 1*d*. Four types of event were recorded, corresponding to the triggering of the center tube alone or in coincidence with any one, two, or three of the outer (guard ring) set of six tubes.

Since most of the γ-rays should fall within a distance of 50 m of the optical axis, their shower "spot" will be generally less elongated than the cosmic-ray-initiated showers, which will not be parallel to the optic axis. If the outer ring is regarded as an anticoincidence, then a class of roughly circular shower spots can be isolated (Weekes and Rieke 1974). The time of arrival and the pulse height of the center tube was recorded during the observing run in 1974 January and February.

TABLE 1

CERENKOV DETECTION-SYSTEM PARAMETERS

Operating Mode	Effective Energy Threshold (GeV)	Collection Area (cm^2)
Single reflector:		
Single beam	100	2.0×10^8
Multiple beams: Type *A*	120	2.4×10^8
Multiple beams: Type *B*	1800	9.6×10^7
Guard ring	150	1.7×10^8
Multiple reflectors ("Double Beam" Technique):		
1.5 m reflector	800	2.7×10^8
10 m and 1.5 m reflector	800	2.7×10^8

NOTE.—Figures given are for effective values of parameters during observations discussed in text; these are all higher than minimum values at the zenith for a dark region of sky.

b) *Multiple Reflectors ("Double Beam" Technique)*

i) *1.5 m Reflectors Only*

In the "double beam" version of the Cerenkov technique (Grindlay 1971, 1972; Grindlay *et al.* 1973; Grindlay, Helmken, and Weekes 1974), an array of three or more Cerenkov detectors is employed to search for anisotropies due to γ-ray-initiated EAS in a similar manner as outlined above but within a smaller solid angle ($\sim 0\overset{\circ}{.}5$ FWHM) about the source. The major difference, however, is that the double beam configuration enables the Cerenkov detection of the muon component in 50–70 percent of the CR-EAS detected, so that this fraction of the cosmic-ray background can be actively rejected.

The first observations with this technique used three 1.5 m reflectors in a fixed pointing mode, i.e., drift scans. Two were separated on a baseline of 70 m and were angled toward one another (typically $0\overset{\circ}{.}3$) so that their 1° FWHM beams intercepted the electron maximum in the longitudinal development of the shower. A third reflector at one end of the base line was pointed so that its 1° beam intersected the mean EAS axis direction (defined by the coincidence detection of the first two detectors) at an angle of $\sim 0\overset{\circ}{.}8$, or nearly the Cerenkov cone opening angle for on-axis particles. Thus the third reflector, which was more sensitive in the ultraviolet, detected light from the penetrating muon component (Grindlay 1974) of particle-induced showers and acted in anticoincidence. The time of arrival of the candidate events was recorded before, during, and after the pulsar transited through the system. The effective energy threshold and the collection area for γ-rays (Table 1) have been estimated from Rieke's (1969) calculations. This operating mode was used in 1971 January, November, and December.

ii) *10 m Reflector and 1.5 m Reflector*

In 1973 February we conducted our first tracking double beam observations of NP 0532 using the 10 m reflector in coincidence with a tracking 1.5 m reflector

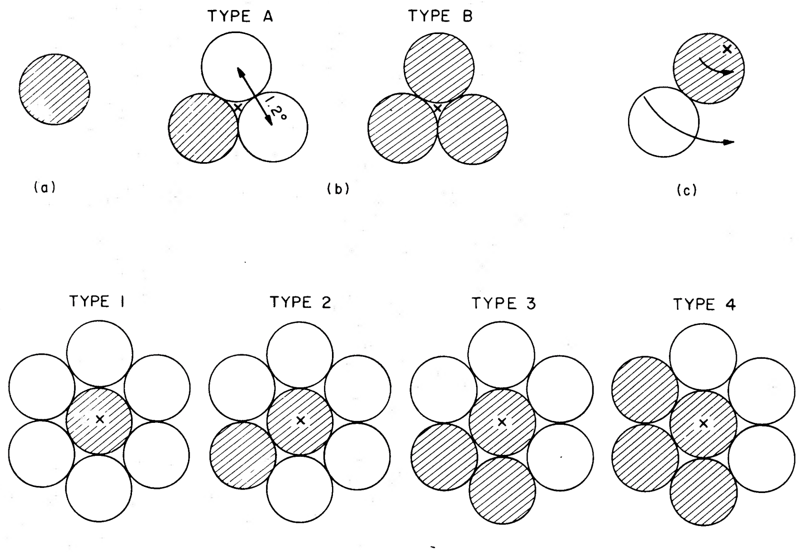

FIG. 1.—Phototube configurations in focal plane of 10 m reflector during observations. (*a*) Single tube (effective field of view of 1°). (*b*) Multiple beam configuration. (*c*) Rotating rejection channel for multiple reflector or "double beam" configuration. (*d*) Guard ring configuration; four event types distinguished.

over a 70 m baseline. The muon component was detected by a photomultiplier (with ultraviolet filter) fixed off axis on the 10 m reflector only. In 1973 December a final series of tracking double beam observations was recorded with somewhat improved muon detection and hence cosmic-ray rejection efficiency. This was achieved by allowing the off-axis phototube to rotate in position angle about the on-axis tube (see Fig. 1*c*), which itself is pointed $\sim 0, 3°$ from NP 0532 to detect EAS at their height (~ 8 km) of maximum development. The off-axis phototube position angle must change slowly, while the source is tracked, to keep the off-axis beam coplanar with the on-axis beams. In order to obtain some spectral information, the pulse height of the on-axis channel was recorded digitally, as were the detected arrival times of both rejected and nonrejected EAS.

The detector parameters (effective energy threshold, collection area) for the various modes used have been estimated from the Cerenkov light distributions calculated by Rieke (1969) and Browning and Turver (1975) for air showers initiated by 10^{11} eV γ-rays (Weekes and Rieke 1974; Weekes 1976); these are summarized in Table 1 for the systems pointing at the zenith. As the zenith angle θ is increased, the energy thresholds and the collection areas increase by the same factor, k^2, where

$$k = [1 - 7.1 \text{ km(h)} \ln (\cos \theta)]/\cos \theta$$

(Chudakov *et al.* 1964).

Prior to 1972 the events were recorded on one channel of a two-channel analog recorder. A 5 kHz signal derived from the ECCo clock at the nearby satellite tracking station was recorded on the second channel. The shower events were interspersed with 1 min markers from the same clock whose absolute time was maintained to better than 100 μ s throughout this period. These data were subsequently digitized, and the final phase analysis was performed on the SAO CDC 6400 computer. After 1973 the time of arrival to 0.1 ms of each shower event was recorded digitally directly.

As a check on our system to detect a period signal from the pulsar, optical observations were made of NP 0532 on the 60 inch (1.5 m) Tillinghast telescope at Mt. Hopkins. The data were taken by cable to the γ-ray data-recording system. These data were taken at irregular intervals up to 1973–1974, after which the optical observations were taken at monthly intervals throughout the γ-ray observations.

III. RESULTS

We present here the final results of arrival time phase analysis of all our observations of NP 0532 since 1969. The phase of the pulsar was derived from the optical observations of Papaliolios and Horowitz (1974) over this entire period. All the data in 1973–1974 have been analyzed in the same manner by interpolating linearly between optical phases computed at each 30 min mark in the data for the locally observable optical phase of NP 0532 at each EAS arrival time. Thus the phase was computed directly for each data time, and not the number of foldings of an assumed period. This latter procedure (period folding) had in fact been used prior to 1973 but was discarded for the most recent observations, since appreciable phase errors can be introduced when long spans (several hours) of data are folded with periods that are changing rapidly. The earlier data were thus also subjected to this more accurate analysis.

The overall accuracy of this phase-analysis method was checked by using it to analyze the optical observations of NP 0532 taken with the Tillinghast telescope at Mt. Hopkins. A typical result is plotted in Figure 2 (lower section), where the predicted phase of the optical main pulse and interpulse is seen to agree well with the observation.

Many of the results obtained with the various observing modes have been reported previously. We present here a summary of these observations for each mode with some revisions for updated estimates of the sensitivity (Table 1) or for revised phase analysis.

a) *Single Beam*

The results of these observations have been published (Helmken *et al.* 1973); using the revised sensitivity estimate these observations give the upper limit shown in Table 2. We have examined each of the 150 runs for nonstatistical fluctuations with phase but find them consistent with Poisson statistics. We have also noted the location of the largest fluctuation in each run but find no tendency for these to group at either the main or interpulse position. [There is some evidence for this kind of effect in the data reported by Porter *et al.* (1975).] However, given the apparently variable pulsed flux and flat energy spectrum we have formed at higher energies (see below), it is possible that a variable pulsed flux could have been present but smoothed out in the 3 year sum of data.

b) *Multiple Beams*

A total of 3.4×10^6 showers (type *A*, or one-fold trigger) were recorded in 78.9 hours of observation in 1973 October–November and 1974 January. In the preliminary analysis, all the data were used; a statistically significant effect was sought at the main or interpulse phase or at any other phase. No such effect was seen, so a 3σ upper limit was derived (Grindlay, Helmken, and Weekes 1974). These upper limits were based on Rieke's (1969) model of the Cerenkov light distribution from a 10^{11} eV γ-ray-initiated shower, which gives the response for a single detector (half angle 0°.5) that is 0°.69 off axis as about 50 percent that of a tube on axis (Weekes and Rieke 1974). The collection areas of the individual channels are independent, so that the total area is 1.5 that of one tube on axis. This agrees with the work of Browning and Turver (1975), but the energy threshold is lower; the upper limit is given in Table 2.

The data were then divided by month, by zenith angle, or by pulse height and again subjected to a phase analysis. The most significant positive effect was seen near the interpulse in the highest pulse-height channels. Further cuts of these data showed that this effect arose almost entirely from type *B* (three-fold) events in January and February at elevation angles greater than 60°. The statistical significance of this effect, which is plotted in Figure 2 (upper section), is estimated as follows:

The integral Poisson probability of getting at least 869 events when the mean (from all bins) for 2 bin intervals is 739 is 1.7×10^{-6}. But a number of choices have been used that decrease this probability: (1) 5 possible bin widths, (2) 50 phases, and (3) 32 divisions of data, giving a chance occurrence probability of 1.4×10^{-2}. It could be argued that the phase is sufficiently close to the interpulse that it can be considered related and that the factor of 50 is an overestimate. A maximum-likelihood test (Hearn 1969; O'Mongain 1973) using 25 phase options (instead of 50) yields (for 0 error in the expected counts) a confidence level of 92 percent that the effect is due to a γ-ray source.

It is difficult to determine from Rieke's (1969) calculations the absolute flux to which this effect corresponds, since we based this configuration on the suggestion of Porter (1973) that the light distribution was actually broader than that of Rieke (because of the effect of the geomagnetic field). Using the results of Browning and Turver (1975), we obtain the values in Table 1 for the effective area and energy threshold. Since only the highest pulse-height channels give this effect (about half the data, since the dynamic range was low and was set to cover the pulse-height range of a single tube), the effective energy was a factor of 2 higher than the threshold. We derive a flux of 1.3×10^{-11} photons cm^2 for an effective energy of 1.8×10^{12} eV.

TABLE 2

RESULTS OF MT. HOPKINS OBSERVATIONS OF NP 0532 AT $E\gamma > 10^{11}$ eV

Mode	Date	Duration (hours)	Energy (GeV)	Flux γ's cm^2 s	Description*
Single beam........	1969 October–1972 April	102	120	1.7×10^{-11}	Upper limit
Multiple beam:					
Type *A*..........	1973 October–November,	48	120	2.0×10^{-11}	Upper limit
	1974 January	30	1800	1.8×10^{-11}	Upper limit
Type *B*..........	1974 January	30	1800	1.3×10^{-11}	Significant at 92% level
Guard ring.........	1974 January–February	30	150	3.0×10^{-11}	Upper limit
Multiple reflector:					
Drift Scans.......	1971 January,	0.7	800	7.4×10^{-12}	Upper limit
	1971 November–December	1.6	800	6.2×10^{-12}	Significant at 85% level
Tracking.........	1973 February,	15	800	2.1×10^{-12}	Significant at 80% level
	1973 December	24	800	4.0×10^{-12}	Significant at 99.97% level

* Upper limits are for an assumed pulsed flux yielding a $\geq 3\sigma$ peak in *any* single phase bin. Confidence levels are based on relative likelihood tests (Hearn 1969; O'Mongain 1973) that the observed effect is due to a γ-ray source at any phase detected above the average of the counts in *all* phase bins. Flux values or limits and energy thresholds are subject to factor of ~ 2 systematic uncertainties.

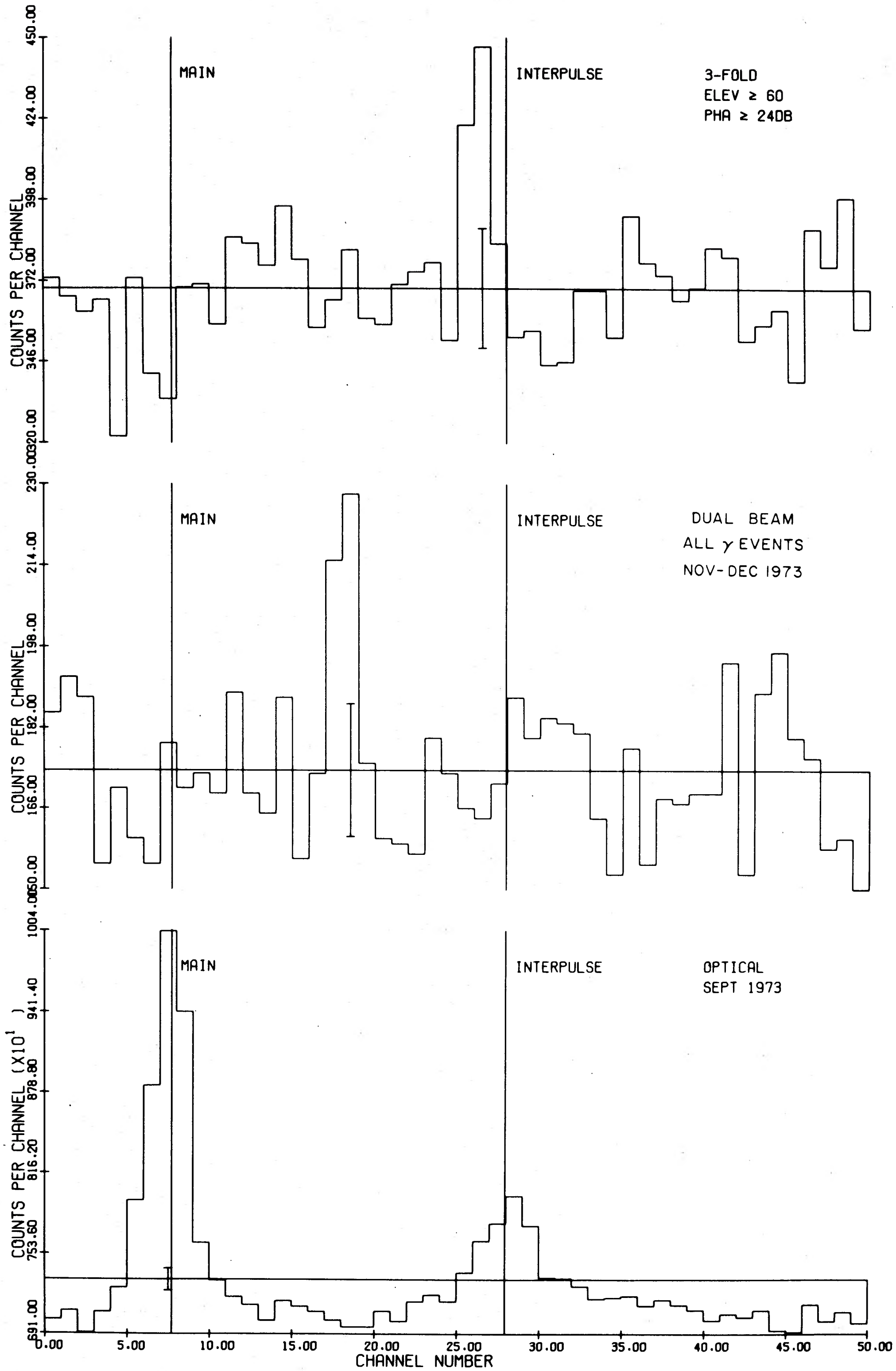

FIG. 2.—NP 0532 phase histograms. (*a*) Phase histogram of three-fold coincidence events in 1974 January. (*b*) Phase histogram of double beam events (nonrejected EAS) in 1973 December. (*c*) Phase histogram of optical data with same system, 1973 September.

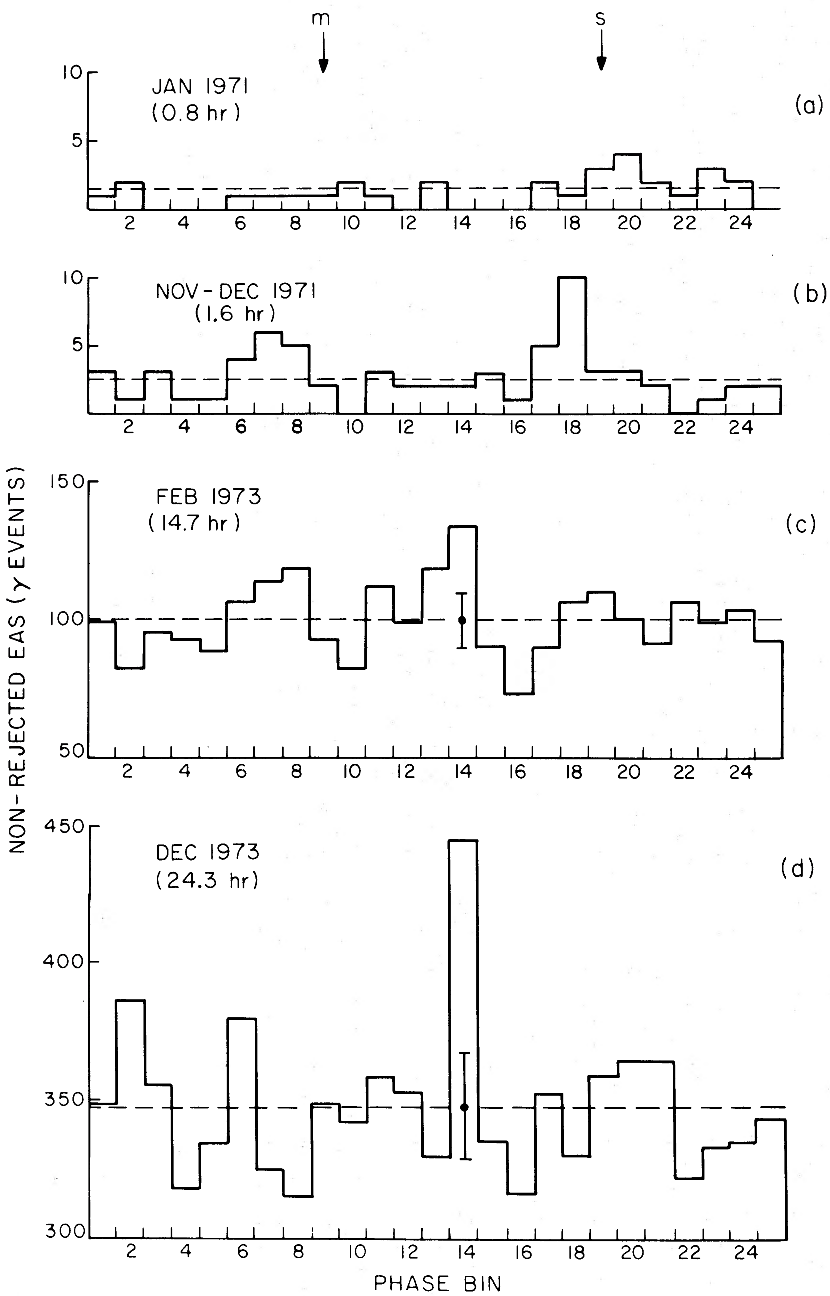

FIG. 3.—Summary of all NP 0532 double beam data. Phase histograms of all nonrejected EAS shown.

This is an extremely high flux and is difficult to reconcile with the upper limits unless some time variability is assumed, as we shall claim below. An upper limit can be derived using the highest pulse-height channels in the single tube data (which excludes three-fold events) taken over the same time interval; the apparent flux and upper limit have virtually the same value (Table 2).

Since the three-fold coincidence requirement is an unusual operating mode, there is even more uncertainty (factor of 3 instead of usual factor of 2) in the flux and energy estimates. The angular size of the shower decreases with zenith angle, so it is understandable that the effect should be most pronounced near the zenith.

c) *Guard Ring*

Thirty hours of data with this configuration were taken in 1974 January and February (Grindlay, Helmken, and Weekes 1974). A phase analysis was made of all the data and with the data divided into each of the four event categories. The data were also divided by pulse height. In none of these cuts of data was there any effect that seemed statistically significant. The most significant upper limit comes from considering all the data at elevations greater than 60° and is given in Table 2.

d) *1.5 m Reflectors*

The events shown in all the double beam histograms [Figs. 2 (middle section) and 3*a*–3*d*] are the nonrejected EAS arrival time phases. The earliest results (1971 January) from the double beam technique hinted at pulsed γ-ray emission from NP 0532 at approximately the phase of the interpulse (Fig. 4*a*) (Grindlay 1971, 1972). Although maximum-likelihood tests (see below) show that this effect alone is not significant, the reanalysis of the 1971 November–December data (Grindlay 1972) shown in Figure 4*b* suggests pulsation at the ~ 85 percent confidence level. Because of the inefficient drift scan mode (~ 1 min source exposure per scan), the total source exposure was less than 2.5 hours; hence the net statistical significance was not great. The apparent fluxes or limits from the 1971 January and November–December observations are listed in Table 2.

e) *10 m Reflector and 1.5 m Reflector*

Preliminary results with this system in which the Crab pulsar was tracked (14.7 hours in 1973 February) have been reported (Grindlay *et al.* 1973). A statistically significant peak was found ($\geqslant 99\%$ confidence level) 2 ms after the phase of the optical main pulse. Subsequent analysis using the refined phase-analysis procedure described above and the discovery of small offsets in absolute time shifted this peak and decreased its significance (Fig. 3*c*).

An additional 24.3 hours of tracking data were recorded in 1973 December with the improved version of the technique outlined above. A phase analysis of these data (nonrejected air showers) is shown in Figure 2 (middle section) (50 bins) and in Figure 3*d* (25 bins). This analysis contained 8675 showers observed on 6 nights from 1973 December 1 to December 22. The most striking feature of the histogram is the appearance of a pulsed feature that is 5.1 σ above the average and located 6.5 ms behind the measured optical main pulse. From the calculation of the double beam collection area and effective energy (Weekes and Rieke 1974), we deduce a pulsed flux

$$F(\geqslant 8 \times 10^{11}\ \text{eV}) = 4.0 \times 10^{-12}\ \text{photon cm}^{-2} \quad (1)$$

for a 1.3 ms bin width and a γ-ray source energy spectral index of $\gamma = 1.6$. The statistical significance of this effect is calculated as follows:

The integral Poisson probability of getting at least 443 events when the mean (from all bins) for a 2 bin interval is 347 is 4.2×10^{-7}. This probability is decreased by the number of choices used in the search for an effect: (1) 5 possible bin widths, (2) 50 phases, and (3) 2 divisions of data, which give an overall probability of 2.1×10^{-4} that the effect seen is a Poisson fluctuation.

Statistically, this is the most significant effect that we have observed in any of the operating modes. The effect appears to be uniformly distributed throughout the 6 nights (1973 December 1–22) of data. That is, it appears over the entire range of zenith angles (0°–40°) and nonrejected pulse heights recorded (dynamic range of 10).

Using the maximum-likelihood analysis (Hearn 1969; O'Mongain 1973) for a pulse at any phase in a 25 bin analysis (Fig. 4) gives the confidence levels for the double beam runs in Table 2. For the 1971 November–December and 1973 February data, the effect is only marginally significant; it is very significant in the 1973 December data, however. The statistical uncertainties are such that all the observations are consistent with a pulsed flux of variable phase and amplitude (on a time scale of months) of $\sim 4 \times 10^{-12}$ photons cm^{-2} s at photon energies $\geqslant 8 \times 10^{11}$ eV.

All the results discussed here, both apparent fluxes and upper limits, have been plotted in Figure 4. We have plotted these results with the large (factor of ~ 2) systematic uncertainties inherent in the determination of absolute energy threshold and collection areas rather than showing only statistical errors to facilitate a more realistic comparison with other measurements of the NP 0532 spectrum. Also shown are the apparent fluxes and upper limits from other experiments (Jennings *et al.* 1974; Porter, Delaney, and Weekes 1975). We also show the extrapolation of the X-ray spectrum of NP 0532 through the observations of McBreen *et al.* (1973) who found definite evidence for a flux at $\geqslant 200$ MeV which was later found (Greisen *et al.* 1975) to be variable in amplitude.

IV. DISCUSSION

The electromagnetic spectrum from the pulsar NP 0532 can be represented by a single power law from radio to medium (~ 1 GeV) γ-ray energies; the results presented here show that an extrapolation of this flux into the 10^{11}–10^{12} eV region overestimates the fluxes by a factor of 20–100. Over the entire range (14 decades), the dominant features in the pulsar light curve are a main pulse followed 13 ms later by an interpulse. Although the relative amplitude of the two pulses varies with energy, the spectrum is remarkable for its uniformity and nonvariability (at least through optical energies). At the level of sensitivity achieved in these observations, there is no evidence for this kind of emission. There is evidence, however, for emission which varies in phase and amplitude at the very high energies.

Any experimental measurement which must invoke time variability to explain a new phenomenon whose existence is not yet firmly established must be treated with a certain amount of caution. *Nonetheless, our 1973 December observations limit the probability to* *only* 2.1×10^{-4} *that NP 0532 was not detected at* $E_\gamma \geq 8 \times 10^{11}$ eV. It is not too unreasonable to expect that the behavior of the pulsar at these very high energies could be quite different from that at lower energies. In addition to the results we have reported that point to a variable pulsed flux, there is some supporting evidence for high γ-ray emission from other atmospheric Cerenkov experiments (Jennings *et al.* 1974; Porter *et al.* 1975). The gas Cerenkov balloon experiment of Greisen *et al.* (1975) has shown that, at $\gtrsim 200$ MeV, the γ-ray spectrum from NP 0532 is variable in amplitude. Observations of the Vela pulsar have shown that the 100 MeV emission is out of phase with the radio emission (Albats *et al.* 1974; Thompson *et al.* 1975); other observations suggest phase variability (Grindlay *et al.* 1975; Frye *et al.* 1974).

The most statistically significant result presented above is that of Figure 2 (middle section), the "double beam" observations in 1973 December. This result shows a narrow ($\lesssim 1.3$ ms) pulse displaced ~ 6.5 ms in phase after the phase of the optical main pulse. We have carefully examined both the data-recording and timing systems as well as analysis programs and conclude that this phase offset must be real, especially since the direct optical observations yielded phases within 0.5 ms of the predictions. The significance of the effect at this phase may be further enhanced, in view of the fact that a small (7.5% of the main pulse) radio pulse feature has been occasionally detected at 408 MHz and 240 MHz with a phase 5.2 ± 0.3 ms after the main pulse (Schonhardt 1971). We note that, since our preliminary report of this result (Grindlay, Helmken, and Weekes 1974), there has been another indication that at high energies pulses may be present at phases other than the main or secondary pulse phases. This is the report (Ryckman *et al.* 1975) that, during ~ 5 min periods in a ~ 6 hour balloon flight exposure on NP 0532, a pulse may have been detected 12 ms before the main pulse (or 6 ms after the secondary pulse) at X-ray energies 35–115 keV.

It should be noted that the phase of the pulse feature in Figure 2 (middle section) corresponds to the region of the light curve that is increasingly "filled in" at increasing X-ray energies. In some of the published hard X-ray light curves, there is even some evidence for pulsed structure in this region. In fact, X-ray "subpulses" have been actually reported at ~ 5 ms delay after both the main and secondary peaks by Ducros *et al.* (1970) and Smathers, Chubb, and Sadeh (1971). Within 3 weeks of the latter observation, the results presented by Laros, Matteson, and Pelling (1973) are also consistent with the presence of these small "subpulses." Individually, these subpulses are only $\sim 2\,\sigma$ peaks in the X-ray data, but together they are significant (Helmken 1975). The fact that now the hard X-ray effect (Ryckman *et al.* 1975) and our γ-phase (Fig. 2, upper and middle sections) are each within about a millisecond of these two phases suggests that they are all real effects characteristic of a common emission region in the pulsar magnetosphere. However, in other X-ray observations (e.g., Bradt *et al.* 1969), these phases are not conspicuous. Thus it seems these subpulses are produced only during "active" periods of typically several weeks' duration and are either not emitted or are smeared out at other times. The result of Ryckman *et al.* (1975) suggests that, even during an extended period when the subpulses are produced, they are sometimes stable only for several minutes.

The statistical evidence for the three-fold coincidence effect is not so strong but is still significant. At face value it appears to conflict with the other results, but the uncertainties in the atmospheric Cerenkov technique are such that it cannot be ruled out.

We now turn to possible interpretations of these results. The fact that the periods of phase variability from radio through very high ($>10^{11}$ eV) energies may occur on a time scale comparable with the timing irregularities of NP 0532 may suggest that changes in the neutron star rotation rate (or "microglitches") are involved. These could perhaps be brought on by changes in the neutron star geology (Ruderman 1969) or particle release from the magnetosphere (Scargle and Pacini 1971). In either case, small changes in the pulsar magnetic field geometry might be expected. These changes might be primarily in the complicated multipole field (Ruderman and Sutherland 1975) near the star or in the more nearly dipole field near the light cylinder for the two glitch models mentioned above. In the first case, perhaps at a certain segment of the polar cap annulus, the B-field radius of curvature increases so that curvature radiation γ-rays and resulting cascade radio and X-ray photons (Roberts and Sturrock 1973) are emitted at the large $\sim 70°$ angle implied by the 6 ms phase lag. In the second case, one might imagine changes in the wrapped-up dipole field at the light cylinder (due to plasma clouds released) so that the extent of the potential gap formed due to electrons escaping changes significantly. Then, if there are particles accelerated in the spark breakdown of the gap (Ruderman and Sutherland 1975) much further out on the curved field lines than usual, they could radiate (curvature-γ-rays, synchrotron radio and X-ray) at the subpulse phase angles. In the first case, the model for the optical pulses of Sturrock, Petrosian, and Turk (1975) would suggest optical subpulses also, whereas they would not be expected for field changes near the light cylinder. The fact that the optical pulse profile has so far been observed to be constant is not conclusive for either picture, since the tests for optical pulse stability (Hegyi, Novick, and Thaddeus 1970; Horowitz, Papaliolios, and Carleton 1972) are limited to only a few observations. We note, however, that the γ-rays which we observe are much more likely to escape pair conversion in the relatively lower B field near the light cylinder.

Finally, we consider the spectral data available for the high-energy results on NP 0532 (Fig. 4). For a Crab distance of 1.7 kpc and a pulse beam size of $\sim 10°$, our flux in equation (1) requires a luminosity of only $\sim 10^{30}$ ergs s^{-1}. This is well within the limits

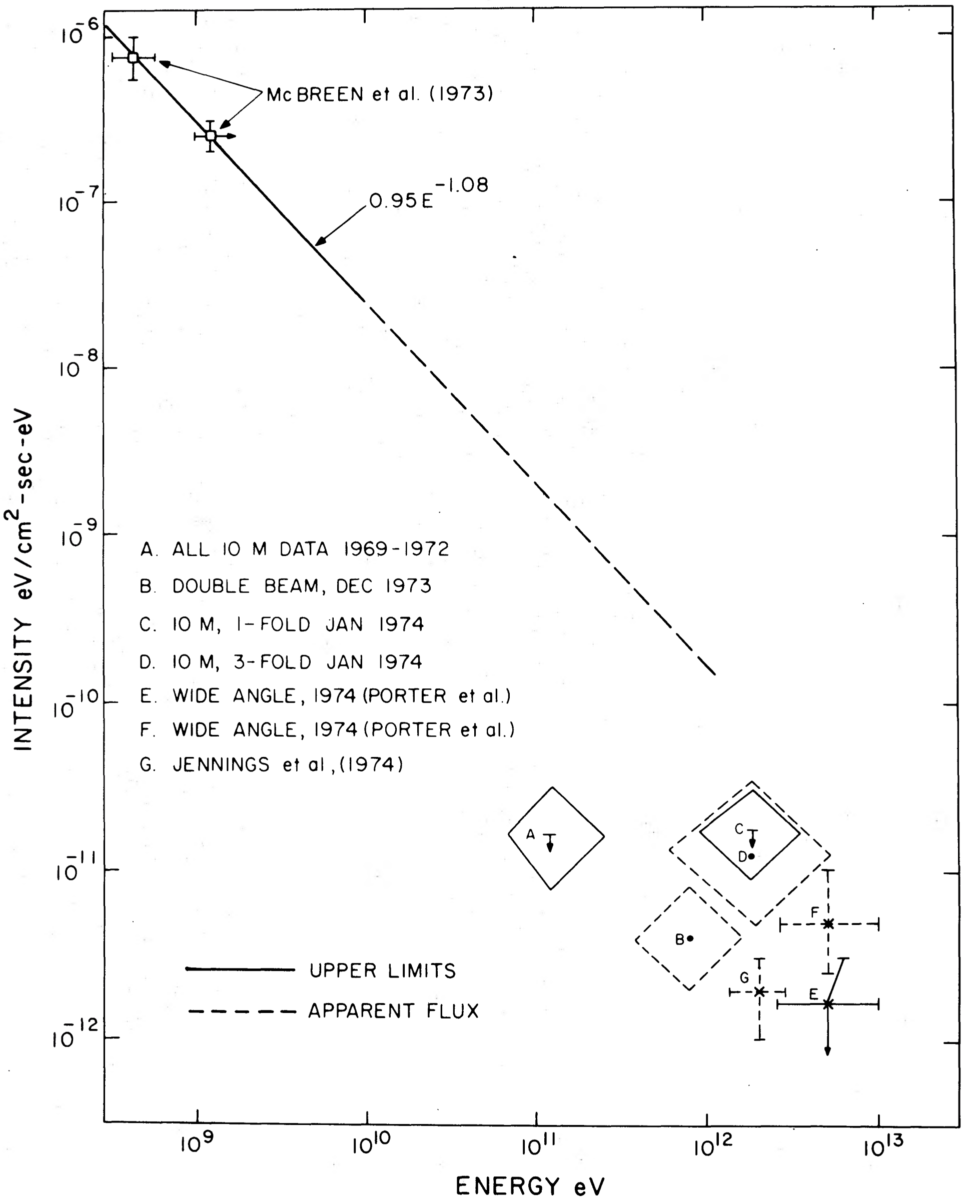

FIG. 4.—Present results plotted together with related experiments. Power law (and dashed extrapolation) shown is taken from McBreen *et al.* (1973) and is a fit to the spectrum of NP 0532 from X-ray energies (10^3 eV)–10^9 eV.

set by either the Sturrock or Ruderman models for the number of $\sim 10^{12}$–10^{14} eV particles accelerated away from the star. The $\sim 10^{12}$ eV γ-ray spectrum may then be due to escaping curvature radiation (as in either model) from the "primary" particles, and produced far enough above the star that the photons are not annihilated in the *B*-field. Alternatively, the pulsed γ-rays we observe could arise from $\sim 10^{12}$ eV cosmic rays accelerated above this star and producing bremsstrahlung while traversing the "cool" matter collected at the "force balance radius" (Roberts and Sturrock 1973). The primary cosmic rays required by our pulsed flux could have a very flat spectrum or be nearly monoenergetic at $\sim 10^{12}$–10^{13} eV and still produce the steeper spectrum of lower-energy pulsar photons in the cascade. Unless the systematic errors in the Cerenkov experiment energy thresholds and collection areas given in Table 1 are very large, the results in Figure 4 exclude the possibility that the results at >100 GeV are on an extrapolation of the NP 0532 spectrum form below 1 GeV. This may indicate that we are able to measure or at least to limit the energy spectrum of primary cosmic rays accelerated within the pulsar light cylinder.

In view of these results, further observations are warranted. The ground-based Cerenkov technique offers many advantages for a long-range monitoring program.

E. Horine assisted throughout this observing program, as did G. H. Rieke, E. O'Mongain, and G. G. Fazio for part of it. We are grateful for many helpful communications from N. A. Porter, E. Turver, and C. Papaliolios.

Our activity has been supported partially by the Smithsonian Institution Hodgkins Fund.

REFERENCES

Albats, P., Frye, G. M., Jr., Thomson, G. B., Hooper, V. D., Mace, O. B., Thomas, J. A., and Staib, J. A. 1974, *Nature*, **251**, 406.
Bradt, H., Rappaport, S., Mayer, W., Nather, R. E., Warner, B., MacFarlane, M., and Kristian, J. 1969, *Nature*, **222**, 728.
Browning, R., and Turver, K. E. 1975, *Proc. 14th International Conference on Cosmic Rays*, Munich, **EA5-1**, 3002.
Chudakov, A. E., Dadykin, V. L., Zatsepin, V. I., and Nesterova, N. M. 1964, *Proc. Lebedev Phys. Inst.*, **26**, 100.
Ducros, G., Ducros, R., Rocchia, R., and Errius, A. 1970, *Nature*, **227**, 152.
Fazio, G., Weekes, T. C., Helmken, H. F., O'Mongain, E., and Rieke, G. H. 1972, *Ap. J. (Letters)*, **175**, L117.
Forman, W., Giacconi, R., Jones, C., Schreier, E., and Tananbaum, H. 1974, *Ap. J. (Letters)*, **193**, L67.
Frye, G. M., Albats, P., Thomson, G. B., Hopper, V. D., Mace, O. B., Thomas, J. A., and Staib, J. A. 1974, *ESLAB Symposium on Gamma Ray Astronomy*, Frascati, p. 265.
Greisen, K., Ball, S. E., Jr., Campbell, M., Gilman, D., Strickman, M., McBreen, B., and Koch, D. 1975, *Ap. J.*, **197**, 471.
Grindlay, J. E. 1971, *Smithsonian Ap. Obs. Special Report*, No. 334.
———. 1972, *Ap. J. (Letters)*, **174**, L9.
———. 1974, *Phys. Rev. D*, **11**, 517.
Grindlay, J. E., Helmken, H. F., and Weekes, T. C. 1974, *ESLAB Symposium on Gamma Ray Astronomy*, Frascati, p. 301.
Grindlay, J. E., Helmken, H. F., Weekes, T. C., Fazio, G. G., and Boley, F. 1973, *Proc. 13th International Conference on Cosmic Rays*, Denver, Vol. **1**, p. 36.
Grindlay, J. E., Helmken, H. F., Hanbury Brown, R., Davis, J., and Allen, L. R. 1975, *Ap. J.*, **201**, 82.
Hearn, D. R. 1969, *Nucl. Instr. and Methods*, **70**, 200.
Hegyi, D., Novick, R., and Thaddeus, P. 1970, in *IAU Symposium 46, The Crab Nebula*, ed. R. D. Davis and F. G. Smith, p. 129.
Helmken, H. F. 1975, *Proc. 14th International Conference on Cosmic Rays*, Munich, **OG3-10**, 128.
Helmken, H. F., Fazio, G. G., O'Mongain, E., and Weekes, T. C. 1973, *Ap. J.*, **184**, 245.
Helmken, H. F., Grindlay, J. E., and Weekes, T. C. 1975, *Proc. 14th International Conference on Cosmic Rays*, Munich, **OG3-9**, 123.
Horowitz, P., Papaliolios, C., and Carleton, N. P. 1972, *Ap. J.*, **172**, 251.
Jelley, J. V. 1958, *Cerenkov Radiation and Its Applications* (New York: Pergamon Press).
Jennings, D. M., White, G., Porter, N. A., O'Mongain, E., Fegan, D. J., and White, J. 1974, *Nuovo Cimento*, **20**, 71.
Laros, J. G., Matteson, J. L., and Pelling, R. M. 1973, *Nature Phys. Sci.*, **246**, 109.
Lyne, A. G., and Thorne, D. J. 1975, preprint.
McBreen, B., Ball, S. E., Jr., Campbell, M., Greisen, K., and Koch, D. 1973, *Ap. J.*, **184**, 571.
O'Mongain, E. 1973, *Nature*, **241**, 376.
Papaliolios, C., and Horowitz, P. 1974, private communication.
Porter, N. A. 1973, *Lettere al Nuovo Cimento*, **8**, 481.
Porter, N. A., Delaney, T., Helmken, H. F., and Weekes, T. C. 1975, preprint.
Porter, N. A., Delaney, T., and Weekes, T. C. 1974, *ESLAB Symposium on Gamma Ray Astronomy*, Frascati, p. 295.
Rankin, J. M., and Counselman, C. C., III. 1973, *Ap. J.*, **181**, 875.
Rankin, J. M., Payne, R. R., and Campbell, D. B. 1974, *Ap. J. (Letters)*, **193**, L71–L74.
Rieke, G. H. 1969, *Smithsonian Ap. Obs. Special Report*, No. 301.
Roberts, D. H., and Sturrock, P. A. 1973, *Ap. J.*, **181**, 161.
Ruderman, M. 1969, *Nature*, **223**, 597.
Ruderman, M. A., and Sutherland, P. G. 1975, *Ap. J.*, **196**, 51.
Ryckman, S., Ricker, G., Scheepmaker, A., Ballintine, J., Doty, J., Downey, P., and Lewin, W. 1975, *IAU Circ. no. 2760*.
Scargle, J. D., and Pacini, F. 1971, *Nature Phys. Sci.*, **232**, 144.
Schonhardt, R. 1970, in *IAU Symposium 46, The Crab Nebula*, ed. R. J. Davies and F. J. Smith, p. 110.
Smathers, H. W., Chubb, T. A., and Sadeh, D. 1971, *Nature Phys. Sci.*, **232**, 170.
Sturrock, P. A. 1971, *Ap. J.*, **164**, 529.
Sturrock, P. A., Petrosian, V., and Turk, J. S. 1975, *Ap. J.*, **196**, 73.
Thompson, D. J., Fichtel, C. E., Kniffen, D. A., and Ögelman, H. 1975, *Ap. J. (Letters)*, **200**, L79.
Weekes, T. C. 1976, preprint.
Weekes, T. C., and Rieke, G. H. 1974, *ESLAB Symposium on Gamma Ray Astronomy*, Frascati, p. 287.

J. E. Grindlay and H. F. Helmken: Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
T. C. Weekes: Smithsonian Institution, Mt. Hopkins Observatory, P.O. Box 97, Amado, AZ 85640