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EVIDENCE FOR TIME VARIABILITY OF PeV ENERGY FLUX FROM CYGNUS X-3: OOTY OBSERVATIONS DURING THE PERIOD 1984–1987

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ABSTRACT

An enhancement in the flux of radiation from Cyg X-3 at energies $>10^{14}$ eV during 1986 April–May has been suggested by several observations. We have studied the observed rate of showers arriving from the direction of Cyg X-3 as a function of time from data collected with the EAS array at Ooty during 1984 June–1987 May. A total of 83 showers were observed in the source bin during the period 1986 March 2–April 21 against an expected number of 56.5. The chance probability for observing such an excess during a 13 week time interval, which covers completely all observations of similar enhancements, has been estimated to be 1%. Ooty observations therefore support earlier suggestions on variability in the PeV flux from Cyg X-3 over time scale of few weeks.

A study of the observed rate of "doubles" in Ooty data has shown that during the last 2 weeks, 1986 April 5–21, of the period of enhanced flux, the number of "doubles" observed from the direction of Cyg X-3 was 10 compared to the expected number of 1.5. Simulations carried out using the observed shower rate and its zenith angle dependence give the chance probability for this excess to be 8×10^{-3}. Ooty observations therefore suggest that a part of the emission at PeV energies was in the form of short duration bursts which lasted only few tens of minutes. Further evidence for short-duration activity was provided by the observation of a burst on 1985 June 19 when five showers were observed from the direction of Cyg X-3 within a time interval of 12 minutes. The chance probability for detection of such a burst in Ooty data on Cyg X-3 is 1.4×10^{-3}. The flux during this intense burst is estimated to be 2.4×10^{-10} cm^{-2} s^{-1} at energies $>2.5 \times 10^{14}$ eV, which is more than two orders of magnitude larger than the time-averaged flux observed at Ooty.

Subject headings: gamma rays: observations — stars: individual (Cygnus X-3)

1. INTRODUCTION

The binary X-ray source Cyg X-3 was first observed at TeV (10^{12} eV) energies by the Crimean group (Vladimirsky & Stepanian 1973) immediately after the large radio outburst in 1972 September. Since then many observations (Weekes 1988; Chadwick, McComb, & Turver 1990) have been made on Cyg X-3, but only a few have succeeded in detecting a signal. This lack of consistency has been interpreted as either due to significant variability in the TeV energy flux from Cyg X-3 with time or due to large statistical fluctuations (Bonnet-Bidaud & Chardin 1988; Chardin & Gerbier 1989). The first detection of Cyg X-3 at PeV (10^{15} eV) energies was reported by Samorski & Stamm (1983) from observations carried out with the Extensive Air Shower (EAS) array at Kiel during 1976–1980. They observed a directional excess of 16.6 showers (4.4 σ) above the average off-source background of (14.4 ± 0.4) showers per bin (4° in right ascension, α, and 3° in declination, δ) for older showers (age ≥ 1.1) at energies above 10^{15} eV. The excess flux showed significant modulation with the 4.8 hr binary period characteristic of Cyg X-3. These results received confirmation from observations by the Haverah Park group (Lloyd Evans et al. 1983a, b) during a partially overlapping period which also showed the 4.8 hr modulation in flux of showers from the direction of Cyg X-3 (9° in α and 6° in δ). Later observations by the same group (Lambert et al. 1985) during 1981–1984 suggested variability of the signal from Cyg X-3 in both phase and amplitude. From observations made with the Ooty EAS array during 1984 June–1986 November, Tonwar et al. (1988) have reported detection of an excess flux of showers from the direction of Cyg X-3 (4° in α and 4° in δ) modulated with the 4.8 hr period. As observed by the Kiel group, the excess observed by the Ooty group was also more prominent among older showers with age ≥ 1.4. A significant variability in the PeV flux from Cyg X-3 was also suggested by Tonwar et al. (1988) from an intercomparison of data segments of approximately 6 months duration each. Observations with EAS arrays operating at Baksan (Alexeenko et al. 1987) and Los Alamos (Dingus et al. 1988a) during the overlapping period in 1986 have not shown steady flux at a level comparable with the time-averaged (1984–1986) flux reported by the Ooty group. However, these observations are consistent with the fact that the directional excess observed by Tonwar et al. (1988) during the last 6 months (1986 June–November) was significantly smaller than in earlier periods.

Dingus et al. (1988a) have reported detection of a signal from Cyg X-3 during a short period of about 45 days, beginning on 1986 April 17. Similarly, Alexeenko et al. (1987) have reported observing the most significant excess from the direction of Cyg X-3 during 1986 May. It is interesting that the short-term flux observed by both the groups showed the 4.8 hr modulation with a significant excess in the phase region, 0.60–0.80, as observed by the Ooty group. It is also of interest to mention here that the flux of showers from the direction of Cyg X-3, observed at Akeno (Teshima et al. 1990) with the 1 km^2 array ($E > 10^{16}$ eV) and the 20 km^2 array ($E > 5 \times 10^{17}$ eV), has shown significant enhancement during the period, 1986 April–May. However, there was no evidence for flux modulation with the 4.8 hr period at these energies. On a shorter time scale, the Fly's Eye group (Baltrusaitis et al. 1987) has reported observation of an episode of enhanced flux from the direction of Cyg

X-3 lasting only a few hours on 1985 June 17 with part of the excess having a binary phase near 0.0.

We report here the results obtained from a detailed study of Ooty data collected during 1984 June–1987 May on temporal variation of PeV flux from Cyg X-3 on different time scales. Relevant details of the experiment and observations are presented in the next section (§ 2). Data analysis and results obtained from this study are discussed in detail in § 3, and the conclusions are summarized in the last section.

2. EXPERIMENTAL DETAILS

Data have been collected with the 24 scintillation detector EAS array operating at the mountain altitude (2200 m) laboratory at Ooty (11°.4 N) in southern India from 1984 June to 1987 May. Showers were selected with a fourfold coincidence between detectors located near the center of the array, and the trigger was optimized for selection of lower energy showers with cores incident over the central part of the array. For each shower, data on relative arrival time and particle density in each detector along with the real time (accuracy 0.5 ms) were recorded. Relevant details of the EAS array, shower trigger, and shower analysis procedures have been published elsewhere (Sreekantan, Tonwar, & Viswanath 1983; Apte et al. 1985; Tonwar et al. 1985; Tonwar et al. 1988). All showers recorded during this period have been analyzed for arrival direction (θ, ϕ, α, and δ), core location (x and y), lateral distribution parameter (shower age s) and shower size (N_e). A total of 6.9×10^6 showers constitute the final data base for studies on cosmic sources at PeV energies. The effective shower size threshold for the array during these observations was 5×10^4 corresponding to an energy threshold of 2.5×10^{14} eV for showers arriving at zenith angles $\theta \geq 29^\circ.4$, which is the angle for Cyg X-3 at meridian transit at Ooty. The angular resolution (σ) of the array has been estimated (Tonwar 1985; Gupta & Tonwar 1991) to be 1°.6. However, it should be noted that the angular resolution of an EAS array is a function of the primary energy, core position, zenith angle, etc. of the shower, and it is realistically not possible to give an exact value for the bin size in α and δ for an optimal selection of showers due to the source. We have chosen, a priori, a bin size $4^\circ \times 4^\circ$ in α and δ for all studies on various sources (Tonwar 1985). In the present case, the $4^\circ \times 4^\circ$ bin centered on Cyg X-3 ($\alpha = 307^\circ.8$, $\delta = 40^\circ.9$) has been designed as the source bin for all studies on this source. Eight α bins at the same declination, four on either side of Cyg X-3 but excluding the α bins adjacent to the source bin, have been used for estimating the background during the present study.

3. DATA ANALYSIS AND RESULTS

Observations on the time-averaged flux from Cyg X-3 based on data collected at Ooty during 1984 May–1986 November were reported by Tonwar et al. (1988). Significant variability in the flux over a time scale of about 6 months was suggested by them from an intercomparison of data segments. Now we have examined Ooty data for possible variation in flux over shorter time scales. Since there is a significant variation in shower rate as a function of the zenith angle of the source bin, analysis has been restricted here to data of only "good" days for both the source bin as well as the eight background bins. A "good" day has been defined for this purpose as a day on which the observations on the source (or the background region) lasted for 240 minutes as the source moved from 32° E to 32° W ($\theta \leq 40^\circ$). During the nearly 3 yr of observations, there were a total of 699 days for the source bin centered on Cyg X-3 with an average shower rate of (1.339 ± 0.044) per day. The average shower rate for the background bins was (1.249 ± 0.015) per day. The observed excess in the shower rate for the Cyg X-3 bin, relative to the background, (0.090 ± 0.046), is of similar magnitude ($\sim 1.9\ \sigma$) as reported by Tonwar et al. (1988) earlier from overall data for the period 1984 June–1986 November without any selection on "good" days, shower size, and shower age.

3.1. *Variation in PeV Flux from Cygnus X-3 over a Few Weeks*

The small value of the shower rate per day, which is primarily due to the small area of the Ooty array and the large zenith angle of Cyg X-3 at Ooty, does not permit a statistically meaningful study of day-to-day variation. Therefore we have studied the variation in the weekly shower rate. Since the present analysis aims at a study of variability in flux with time, the shortest time interval which yields a statistically meaningful number of showers is to be preferred. With an average shower rate of about 1.25 per day, a week is a naturally preferred time interval as the average number of showers observed per week is 8.75. Note that a period of 1 week (7 "good" days) does not necessarily consist of 7 consecutive calendar days as there were occasionally shorter runs on some days due to either instrumentation failures or electrical power interruptions. These days were distributed quite uniformly over the three years of observations.

Figure 1*a* shows the variation of this rate over the entire observation period consisting of 99 such time intervals. The arrow mark shown in the figure indicates the week starting on 1986 April 5. The variation of the mean rate for the eight background α bins is shown in Figure 1*b*. It may be seen from the figure that the mean background rate did not remain constant over the 3 yr period and varied slightly with time. This was due to a slow drift in single particle calibrations for detectors used for selection of showers. However, since the source and the background (α, δ) bins observe showers almost concurrently, the effect of the drift in shower rate is identical for both regions. Therefore, it is more appropriate to study the variation of the excess shower rate in the source bin relative to the background. This plot is shown in Figure 2. Though no significantly large excess is seen in this figure for any individual week, the excess seen in 5 out of 6 consecutive weeks is easily noticeable around 1986 April 5 when several other groups (Akeno, Baksan, and Los Alamos) have reported observing a signal from Cyg X-3. This excess may be seen more prominently in Figure 3 which gives a plot of same data for time intervals of 6 weeks. Data shown in this figure apparently suggest that the PeV flux from Cyg X-3 was larger during the period, 1986 March 2–April 21 (ninth bin). A total of 83 showers were observed in the source bin during the period 1986 March 2–April 21. This may be compared with an expectation of 52.5 which is based on the mean rate of 1.249 per day determined from the eight background bins over the period of 3 years.

Simulations have been carried out to evaluate the significance of this excess in any combination of data of contiguous weeks during the observation period of 99 weeks. Using the mean weekly shower rate of 8.74, the number of showers expected in each of the 99 weeks were generated from the Poisson distribution. This set of simulated data for 99 weeks forms one "Ooty observation." Using this data set, 99 1 week, 98 2 week, 97 3 week, ..., and one 99 week combinations were formed by adding successive weeks of data. All these (4950)

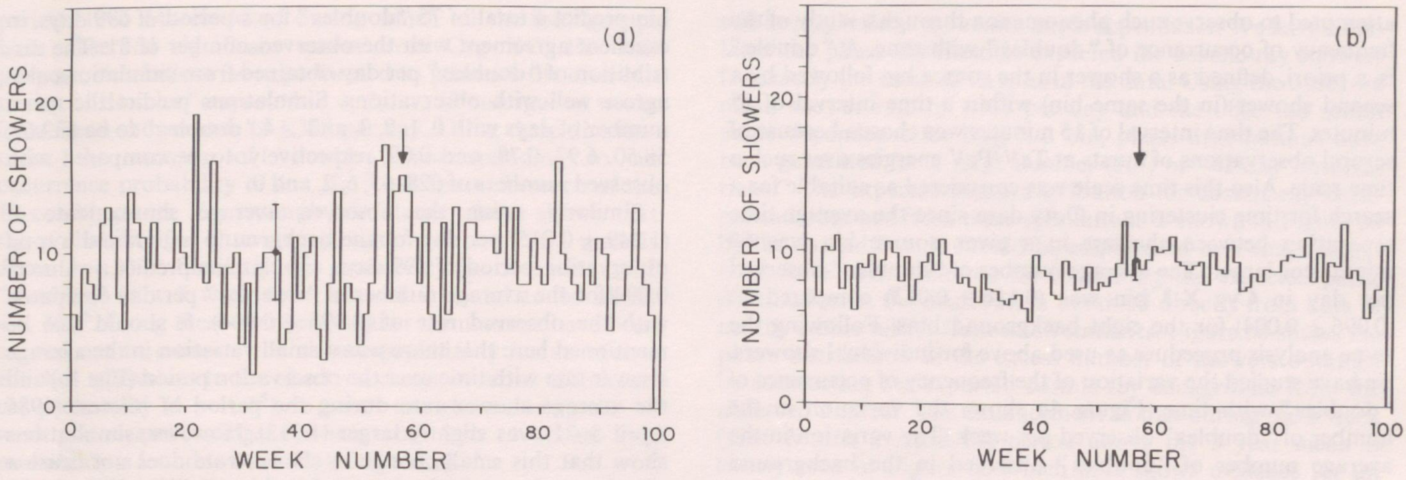

FIG. 1.—Variation in the shower rate per week with time (*a*) from the direction of Cyg X-3, and (*b*) from the background region. The arrow indicates the week starting on 1986 April 5.

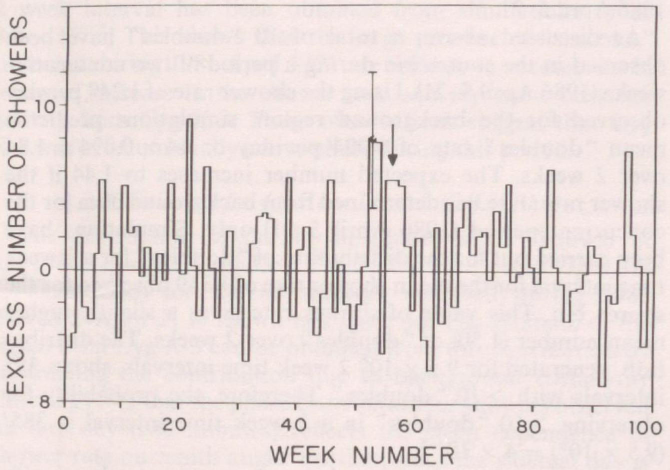

FIG. 2.—Variation in the excess number of showers observed per week in the source bin relative to the average number observed in the background region as a function of time. The arrow indicates the week starting on 1986 April 5.

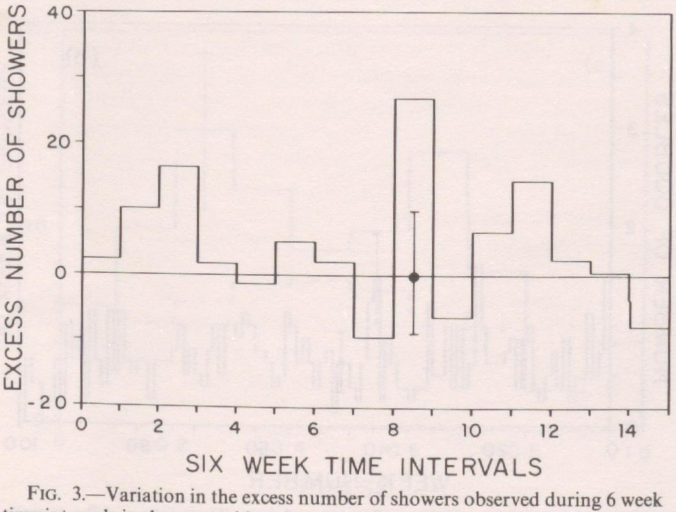

FIG. 3.—Variation in the excess number of showers observed during 6 week time intervals in the source bin relative to the average number observed in the background region as a function of time.

combinations were then scanned to detect any occurrence of an equivalent excess $\geq 4.2\ \sigma$ $[(83 - 52.5)/(52.5)^{1/2}]$ relative to the mean for the corresponding combination. A total of 311 of 10^4 "Ooty observations" showed an equivalent excess $\geq 4.2\ \sigma$. Therefore the probability for observing such an excess in any combination of data is $(3.11 \pm 0.18) \times 10^{-2}$. It should be emphasized here that since the real data were not scanned for the excess in this manner, this estimate of the probability is an upper limit.

This value of the chance probability is also an overestimate due to the fact that the observation period at Ooty, 1986 March 2–April 21, overlaps partially with the period (1986 April–May) when three other groups (Akeno, Baksan, and Los Alamos) have reported observing excess number of showers from Cyg X-3. A realistic estimate for the chance probability can be obtained by considering a time interval of only 13 weeks (1986 March–May) which covers completely the periods of observations of excess flux by all the four groups (Akeno, Baksan, Los Alamos, and Ooty). For this purpose, the mean weekly rate for the background bins has been determined to be 9.42 for the 6 week period 1986 March 2–April 21. Following the same procedure as described above and using the mean weekly shower rate of 9.42, a data set for 13 weeks, which forms one "Ooty observation," was generated. Using this data set, 13 1 week, 12 2 week, ..., and one 13 week combinations were formed. All these (91) combinations were then scanned to detect any occurrence of an equivalent excess $\geq 3.5\ \sigma$ $[(83 - 56.5)/(56.5)^{1/2}]$ relative to the average for the corresponding combination. A total of 1133 of 10^5 "Ooty observations" showed the required excess. Therefore, the chance probability of observing an excess $\geq 3.5\ \sigma$ to occur anywhere during this 13 week period and lasting anywhere from 1 to 13 weeks is $(1.13 \pm 0.03) \times 10^{-2}$. These results therefore provide support to the hypothesis that the PeV flux from Cyg X-3 varies significantly over a time scale of a few weeks.

3.2. *Variation in PeV Flux from Cygnus X-3 over Tens of Minutes*

Since observations on X-ray binaries at TeV and PeV energies (Chadwick et al. 1990; Dingus et al. 1988b; Gupta et al. 1990) have shown evidence for significant flux enhancements over time intervals as short as several minutes, we have attempted to observe such phenomenon through a study of the frequency of occurrence of "doubles" with time. A "double" is, a priori, defined as a shower in the source bin followed by a second shower (in the same bin) within a time interval of 15 minutes. The time interval of 15 minutes was chosen because of several observations of bursts at TeV/PeV energies over such a time scale. Also this time scale was considered as suitable for a search for time clustering in Ooty data since the average time separation between showers in a given source bin was 60 minutes or larger. The average number of "doubles" observed per day in Cyg X-3 bin was (0.116 ± 0.013) compared to (0.096 ± 0.004) for the eight background bins. Following the same analysis procedure as used above for individual showers, we have studied the variation of the frequency of occurrence of "doubles" with time. Figure 4*a* shows the variation in the number of "doubles" observed per week. The variation in the average number of "doubles" observed in the background region is shown in Figure 4*b*. It is interesting to note from Figure 4*a* that two consecutive weeks (1986 April 5–13 and April 14–21) show a significantly larger number of "doubles" in the source bin compared to the background. A total of 10 "doubles" have been observed in the source bin during this period (1986 April 5–21), compared to 1.34 expected from data for the background region. It is to be noted that this large increase in the observed "doubles" rate for showers in Cyg X-3 bin coincides in time with the period (1986 March 2–April 21) which showed a significant increase in the shower rate as discussed above and with the period (1986 April–May) when three other groups (Alexeenko et al. 1987; Dingus et al. 1988a; Teshima et al. 1990) observed significant enhancements in flux of ultra–high-energy radiation from Cyg X-3.

The probability for the occurrence of a "double" cannot be evaluated directly by using the average shower rate per day since the shower rate varies significantly over the 240 minutes of observation during a day due to its sensitivity to the zenith angle of the source. Therefore, we have carried out Monte Carlo simulations to estimate the frequency of occurrence of "doubles" using the observed shower rate and the observed variation of shower rate with zenith angle, simulating exactly the zenith angle sweep by the source region centered on the declination of Cyg X-3. Simulations carried out using the observed shower rate of (1.339 ± 0.044) per day for the source bin predict a total of 75 "doubles" for a period of 699 days, in excellent agreement with the observed number of 81. The distribution of "doubles" per day obtained from simulations also agrees well with observations. Simulations predict the mean number of days with 0, 1, 2, 3, and ≥4 "doubles" to be 632.66, 58.50, 6.97, 0.78, and 0.09, respectively, to be compared with observed numbers of 628, 63, 6, 2, and 0.

Similarly, using the observed average shower rate of (1.249 ± 0.015) per day for the background region and a total observation period of 699 days, simulations predict a value of 0.094 for the average number of "doubles" per day compared with the observed rate of (0.096 ± 0.004). It should also be mentioned here that there was a small variation in the average shower rate with time over the observation period (Fig. 1*a*) and the average shower rate during the period of interest (1986 April 5–21) was slightly larger (1.313). However, simultations show that this small change in shower rate does not cause a significant change in the expected number (0.103) of "doubles" per day. The preceding discussion shows that simulations closely reproduce the observations on "doubles" in the source as well as the background region except for the 2 week period 1986 April 5–21.

As discussed above, a total of 10 "doubles" have been observed in the source bin during a period of two consecutive weeks (1986 April 5–21). Using the shower rate of 1.249 per day observed for the background region, simulations predict a mean "doubles" rate of 0.094 per day or 14 × 0.094 = 1.34 over 2 weeks. The expected number increases to 1.44 if the shower rate (1.313) is determined from background data for the concurrent period (1986 April 5–21) only. Simulations have been carried out for the distribution of "doubles" for a 2 week time interval for the mean shower rate of 1.339 observed for the source bin. This value of shower rate gives a slightly higher mean number (1.50) of "doubles" over 2 weeks. The distribution, generated for 9.5×10^6 2 week time intervals, shows 385 intervals with ≥10 "doubles." Therefore, the probability for observing ≥10 "doubles" in a 2 week time interval is $385/(9.5 \times 10^6) = 4 \times 10^{-5}$.

Simulations have been carried out to estimate the significance of observing an equivalent excess (probability 4×10^{-5}) for any combination of data from 1 to 13 contiguous weeks. Note that the duration of 13 weeks covers completely the

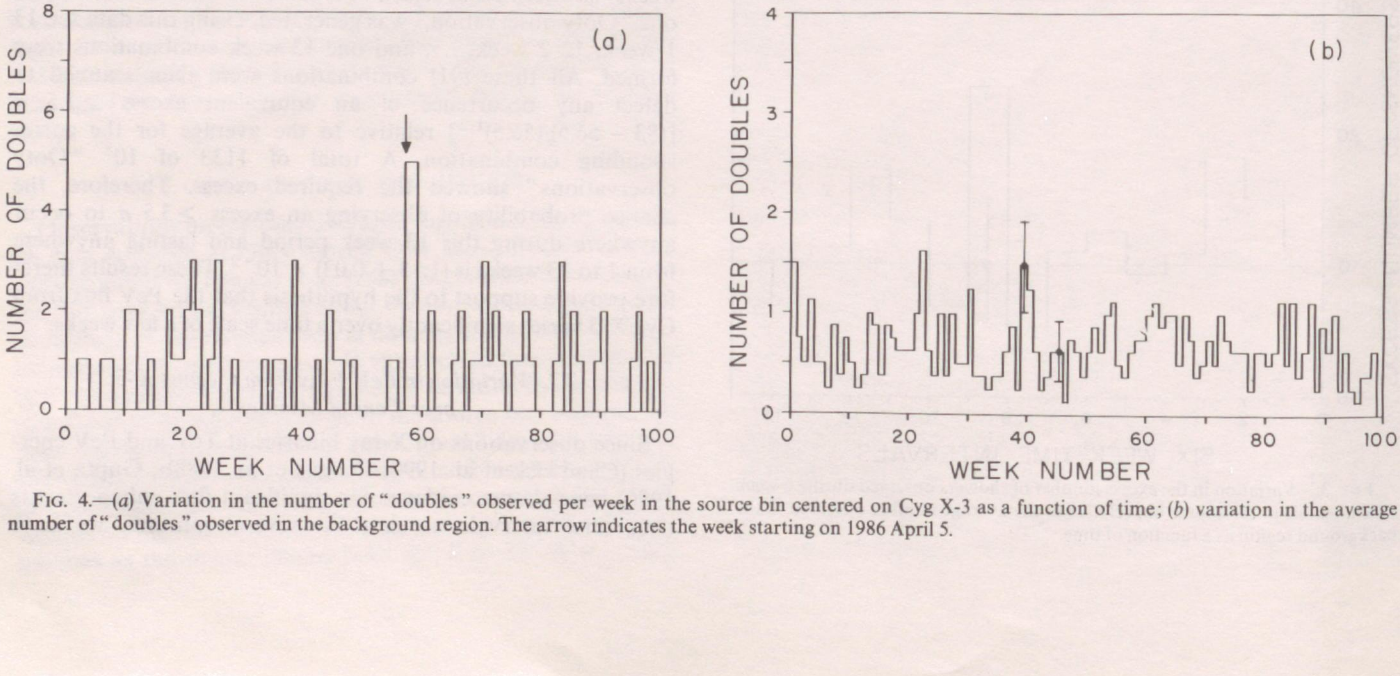

FIG. 4.—(*a*) Variation in the number of "doubles" observed per week in the source bin centered on Cyg X-3 as a function of time; (*b*) variation in the average number of "doubles" observed in the background region. The arrow indicates the week starting on 1986 April 5.

period (1986 March–May) during which all the four groups have observed significant excess from Cyg X-3. For this purpose, simulations were performed to generate the distributions of "doubles" expected in 1, 2, ..., 13 contiguous weeks for a mean shower rate of 1.339 per day. Using these distributions, the number of "doubles" corresponding to an occurrence probability of 4×10^{-5} was found for each of the 13 combinations. For example, simulations have shown that the probability for observing ≥eight "doubles" in 1 week is about 4×10^{-5}. Similarly, the probability for observing ≥19 "doubles" in a 7 week time interval is found to be about 4×10^{-5}. Using these numbers, further simulations have been carried out to estimate the chance probability for an excess, which is equivalent to the observed excess in terms of individual probability (4×10^{-5}), to occur anywhere during the 13 week period and lasting anywhere from 1 to 13 weeks. This probability is found to be $(1.07 \pm 0.03) \times 10^{-3}$.

It should also be mentioned here that the shower rate per day was higher (2.07 ± 0.38) in the source bin during the 2 week time interval (1986 April 5–21) due to a signal from Cyg X-3. The probability for observing ≥10 "doubles" during this 2 week interval has been obtained from simulations to be 8.0×10^{-3}. This shows that the large number of "doubles" observed during 1986 April 5–21 are difficult to account for in terms of increase in the shower rate and represent burstlike activity from Cyg X-3. These observations suggest that Cyg X-3 was in an unusually active phase during this period.

3.3. *Evidence for 4.8 Hour Modulation in Flux*

The distribution of the 4.8 hr phase values (Tonwar et al. 1988, $P = 0^{\mathrm{d}}.199968338$, $\dot{P} = 1.02 \times 10^{-9}$, and $T_0 =$ JD 2,440,949.8965) for the 83 showers observed during 1986 March 2–April 21 is shown in Figure 5*a*. The estimate of the signal from Cyg X-3 can be obtained from this distribution by subtracting the contribution due to background cosmic-ray showers. Note that the phase distribution for showers observed on any day (240 minutes) reflects the steep dependence of shower rate on zenith angle. Further, since the sidereal day is nearly an integral multiple of the orbital period of Cyg X-3, a given phase bin occurs at nearly the same zenith angle for several weeks. Therefore the observed phase distribution for showers collected even over 6 weeks (1986 March 2–April 21) still largely reflects the zenith angle dependence. We have simulated the phase distribution expected for cosmic-ray showers for exactly the same 42 days as in the data. Using the observed mean shower rate of 1.339 per day and the observed zenith angle dependence for Cyg X-3 bin, phase distributions have been generated for a large number (10^5) of "42 day observations." The expected mean distribution for cosmic-ray background obtained from these simulations is shown in Figure 5*a* by the dashed line. It should be emphasized here that simulations have been preferred for estimating the expected phase distribution as the distribution obtained directly from data of nearby α bins suffers from small statistics. Figure 5*b* shows the phase distribution of the excess number of showers obtained by subtracting the expected cosmic-ray background from the observed number. The enhancement in flux during the 6 week (1986 March 2–April 21) period above the 3 year mean is clearly seen in Figure 5*b* which also shows evidence for an excess in the expected phase regions, 0.2–0.3 and 0.6–0.7 (Samorski & Stamm 1983; Lloyd-Evans et al. 1983b; Lambert et al. 1985; Alexeenko et al. 1987; Dingus et al. 1988a; Tonwar et al. 1988; Chadwick et al. 1990). This association of the excess with phase regions, 0.2–0.3 and 0.6–0.7, is equally interesting in the case of "doubles" observed during 1986 April 5–21, as may be seen from Figure 6. Note that only the phase of the first shower of each "double" has been plotted in Figure 6 since the binary phase of Cyg X-3 changes by only 0.05 in 15 minutes.

3.4. *Showers with Age ≥ 1.1*

It should be noted here that during this study of the variation of shower rate and the "doubles" rate per week, no selection has been made on shower age. Observations by Samorski & Stamm (1983) and Tonwar et al. (1988) have shown earlier that a selection of showers with large value of age enhances the signal from Cyg X-3 relative to the background. Similar enhancement has also been observed for pulsed signal from the Crab pulsar (Gupta et al. 1991). It has been observed that the number of showers with age ≥1.1 (median value) observed in the source bin centered on Cyg X-3 during 1986 March 2–April 21 was 49 compared to the average of 31.2 in the background region. Though the signal-to-background ratio has increased with age cut, from 0.47 (26.5/56.5) to 0.57 (17.8/31.2), the excess has gone down slightly, from 3.5 σ to 3.2 σ. The

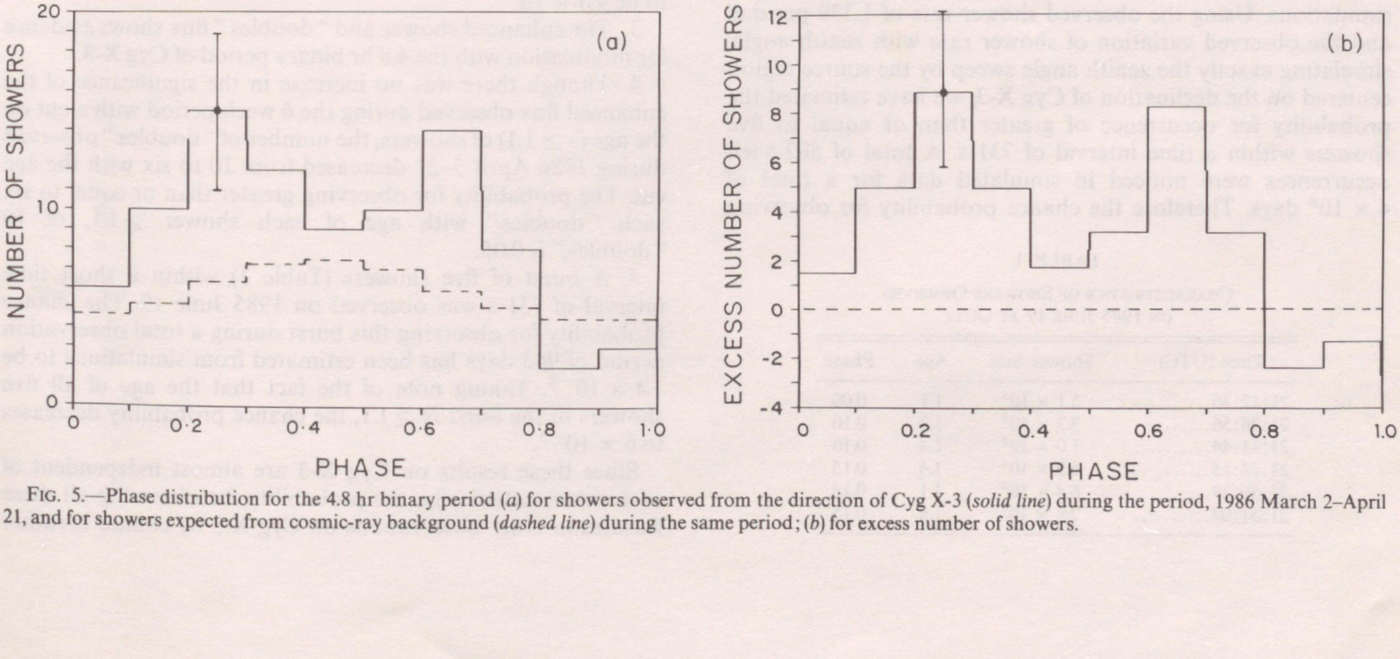

FIG. 5.—Phase distribution for the 4.8 hr binary period (*a*) for showers observed from the direction of Cyg X-3 (*solid line*) during the period, 1986 March 2–April 21, and for showers expected from cosmic-ray background (*dashed line*) during the same period; (*b*) for excess number of showers.

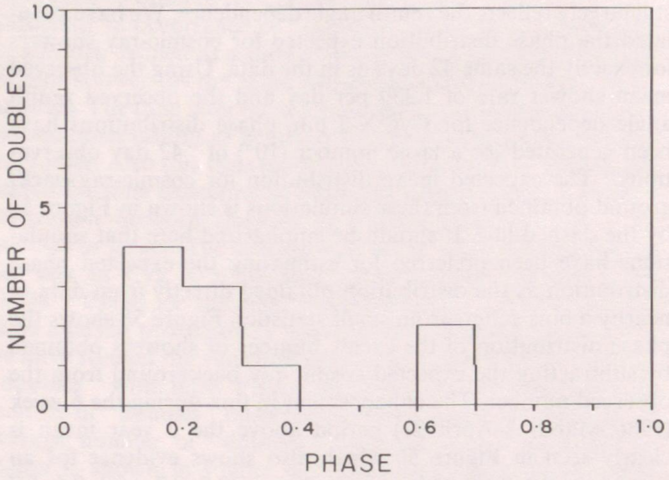

FIG. 6.—Phase distribution for the 4.8 hr binary period for the 10 "doubles" observed during 1986 April 5–21.

phase distribution for old showers is similar to the distribution shown in Figure 5*a* for all showers. In case of "doubles," the number observed during 1986 April 5–21 decreases from 10 to six. Of the 17 showers observed in the source bin during 1986 April 5–21, that form the 10 "doubles," 14 have age ≥1.1. Of these 14 showers, 11 make up the six "doubles." The probability for observing six "doubles" with the age of each shower ≥1.1 is determined to be 0.05 from simulations.

3.5. *Observation of a Short Duration Burst on 1985 June 19*

Ooty observations on the enhanced flux of "doubles" during the period 1986 April 5–21, interpreted as due to the occurrence of short duration bursts, lead to the expectation that larger bursts may also occur though with reduced frequency. A large burst would be detected as a burst of many showers within a short interval of time. We have searched for clusters of "doubles" in the source bin centered on Cyg X-3 in the complete data base, including days when the observation period was shorter than 240 minutes due to some interruptions. We have observed an unusual occurrence of five showers (Table 1) within a short time interval of 731 s on 1985 June 19. The probability for such an event to occur due to random fluctuations has been estimated from Monte Carlo simulations. Using the observed shower rate of 1.339 per day and the observed variation of shower rate with zenith angle, simulating exactly the zenith angle sweep by the source region centered on the declination of Cyg X-3, we have estimated the probability for occurrence of greater than or equal to five showers within a time interval of 731 s. A total of 582 such occurrences were noticed in simulated data for a total of 4×10^8 days. Therefore the chance probability for observing the burst of 1985 June 19 is

$$943 \times 582/(4 \times 10^8) = 943 \times 1.46 \times 10^{-6} = 1.4 \times 10^{-3}$$

for a total observation period of 943 days. It is also noteworthy that the age of all six showers (Table 1) observed on 1985 June 19 is ≥1.1. The median value of age for showers observed at Ooty is 1.10. The chance probability has been obtained from simulations, following the procedure described above, to be 6×10^{-5} for observing a 731 s burst of five showers, with the additional contraint that the age of each shower be ≥1.1. It should be mentioned here that this burst was observed at Ooty within 36 hr of an episode of enhanced flux detected by the Fly's Eye group (Baltrusaitis et al. 1987) on 1985 June 17. The 4.8 hr phase distribution for showers observed by the Fly's Eye group showed clustering around phase value of 0.0. Interestingly, showers in the burst observed on 1985 June 19 at Ooty also have phase value close to 0.1. This is different from the time-averaged flux (Tonwar et al. 1988) which has shown an excess in phase region, 0.6–0.8. The estimated flux, 2×10^{-10} cm^{-2} s^{-1} at energies $>2.5 \times 10^{14}$ eV during the 12 minute duration of the burst detected at Ooty is much larger, by more than two orders of magnitude, compared to the time-averaged flux of 7.2×10^{-13} cm^{-2} s^{-1} reported by Tonwar et al. (1988).

TABLE 1

CHARACTERISTICS OF SHOWERS OBSERVED ON 1985 JUNE 19 AT OOTY

Time (UTC)	Shower Size	Age	Phase
21:12:36..........	5.1×10^5	1.1	0.00
21:38:56..........	3.3×10^5	1.3	0.10
21:41:44..........	1.0×10^5	1.4	0.10
21:44:15..........	6.9×10^4	1.4	0.15
21:50:39..........	6.4×10^4	1.1	0.15
21:51:07..........	2.9×10^5	1.4	0.15

4. DISCUSSION AND CONCLUSIONS

A detailed analysis of Ooty data collected during 1984 June–1987 May on the variation of shower rate and the "doubles" rate with time has yielded the following results:

1. There was a significant enhancement in the flux of showers from the direction of Cyg X-3 during the period 1986 March 2–April 21 which was nearly coincident in time with similar enhancements seen in several other experiments. The chance probability for observing this enhancement anywhere during the 13 week period, which covers completely the periods of observation of flux increase in all four experiments (Akeno, Baksan, Los Alamos and Ooty), and lasting anywhere from 1 to 13 weeks has been estimated from simulations to be $(1.13 \pm 0.03) \times 10^{-2}$.
2. There was a significant increase in the "doubles" rate during the last 2 weeks, 1986 April 5–21, within the period of enhanced flux. The probability for observing ≥10 "doubles" during this 2 week interval has been obtained from simulations to be 8.0×10^{-3}.
3. The enhanced shower and "doubles" flux shows evidence for modulation with the 4.8 hr binary period of Cyg X-3.
4. Though there was no increase in the significance of the enhanced flux observed during the 6 week period with a cut on the age ($s \geq 1.1$) of showers, the number of "doubles" observed during 1986 April 5–21 decreased from 10 to six with the age cut. The probability for observing greater than or equal to six such "doubles" with age of each shower ≥1.1, of 10 "doubles," is 0.05.
5. A burst of five showers (Table 1) within a short time interval of 731 s was observed on 1985 June 19. The chance probability for observing this burst during a total observation period of 943 days has been estimated from simulations to be 1.4×10^{-3}. Taking note of the fact that the age of all five showers in the burst is ≥1.1, the chance probability decreases to 6×10^{-5}.

Since these results on Cyg X-3 are almost independent of each other statistically, the probability for observing all these features in Ooty observations on Cyg X-3 by chance is rather small. Ooty observations, therefore, lead to two significant conclusions:

1. The flux of radiation from Cyg X-3 at PeV energies is variable with time with significant enhancements occurring over a time scale of a few weeks.

2. The emission during these periods is partly in the form of short duration bursts lasting a few tens of minutes. The enhanced flux during the period, 1986 March 2–April 21, has been estimated to be $(5.5 \pm 2.0) \times 10^{-12}$ cm^{-2} s^{-1} at energies $> 2.5 \times 10^{14}$ eV, which was nearly 8 times larger than the time-averaged flux of 7.2×10^{-13} cm^{-2} s^{-1} observed during 1984–1986 (Tonwar et al. 1988). The flux during the 12 minute burst, observed on 1985 June 19, was 2×10^{-10} cm^{-2} s^{-1} at energies $> 2.5 \times 10^{14}$ eV which is larger by more than two orders of magnitude compared to the time averaged flux.

A further study on these interesting features of the emission from Cyg X-3 at PeV energies is in progress now with a new 90 detector array at Ooty. A study of the muon content of showers would be carried out with a 200 m^2 area muon detector ($E_\mu > 1$ GeV) to get information on the nature of the PeV energy radiation from Cyg X-3. The muon detector became operational in 1991 May.

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TeV and PeV radiations from the Crab

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The Crab nebula, which is the remnant of a supernova explosion that occurred in 1054, is one of the most fascinating objects in the sky that is extensively studied in all the bands of the electromagnetic spectrum. The source of energy from this object is the fast spinning central magnetized neutron star. The environment is most suitable for it to be a source of very high energy cosmic rays accelerated in the magnetosphere of the pulsar. Detection of very high energy gamma rays from this object is the only sure way to confirm. In the last decade, intense efforts have been on by several groups to detect these very high energy gamma rays. Due to a recent technical breakthrough, the Crab nebula is now confirmed to be a steady gamma-ray emitter in the TeV energy region. The evidence for a steady but pulsed TeV and PeV emission from the pulsar is not so firm. However, TeV and PeV emissions from the pulsar appear to be transient in nature. A recent simultaneous observation of a PeV energy burst by four different groups has features which have important implications for the acceleration of particles, production of gamma rays and their behaviour at very high energies.

The present status of TeV and PeV observations on the Crab and the models proposed for gamma-ray emission at these energies are reviewed and the anomalies in the steady, pulsed and transient modes highlighted to focus attention on the types of future observations and modelling that are required.

ACCORDING to the chronicles left by the Royal Astronomer, Yang-Wei-Te, of the Sung Dynasty in China, "on a Chi-Chou day of the 5th month of the first year of the Chi-Ho period, a 'guest star' suddenly appeared at the southeast of Thien-Kaun measuring several inches". The star was visible for 23 days during day time and was as bright as Venus and could be seen for 650 nights. This celestial event according to Julian calendar happened on the 4 July 1054 AD in the constellation Taurus and has been identified with the explosion of a star, resulting in a supernova remnant, the Crab nebula, which with the present day telescopes is seen as a hot web of gas with bright reddish filaments. Optical observations, taken a decade apart, have revealed the expanding nature of the hot mass with rather high velocities. It has now been estimated that the supernova reached a maximum visual magnitude of -6.5 to -7 and with the distance estimate of 2 kiloparsecs the absolute magnitude must have been at least -16.5. One of the most powerful radio sources, Taurus A, is identified with the nebula.

The radiation from the nebula is polarized in the optical, radio and even in the 3.15-cm radio wave region. Schklovsky[1] pointed out in the early fifties that the high degree of optical polarization could be accounted for by synchrotron process requiring the presence of very high energy ($>10^{12}$ eV) electrons gyrating round the magnetic fields ($\sim 10^{-4}$ G) in the filaments. In 1960 Cocconi[2] suggested that since electrons of such high energy cannot arise from nuclear-decay processes, a mechanism of acceleration of particles to high energies must be operative in the nebula. If such a mechanism was indeed present, there was no reason why protons could not be accelerated to high energies too. Presence of such high-energy protons meant that these particles in their nuclear collisions with the filamentary matter could produce charged and neutral pions. Large-scale efforts to look for high-energy (hundreds of GeV) gamma rays from the decay of neutral pions were mounted in the late fifties. The survey also included other supernova remnants. Two methods were employed for this purpose depending upon the energy of the gamma rays of interest. The first method, which has come to be known as the Air Cerenkov Technique (ACT), used the pool of Cerenkov photons produced by the cascade electrons in traversing the atmosphere. The pool of light was collected by a system of search light mirrors mounted on orientation platforms. These could be pointed in the direction of any suspected source and made to follow the source for several hours; the photomultipliers at the foci of the mirrors recorded the intensity of Cerenkov radiation. The requirement of coincident pulses in several mirrors, aligned parallel to each other, reduced the background counting rates, essentially due to star light. This method is used in the TeV (10^{12} eV) energy region, where the number of cascade particles reaching the observation level is too small to be detected. In the second method used at PeV (10^{15} eV) energies, where the number of cascade particles reaching the observation level is large enough to be recorded, extensive air shower (EAS) arrays are employed. In these arrays, a large number of unshielded plastic scintillators are set up over a large area for recording the densities of shower particles, from which the energy of the primary particle is estimated. The arrival times of the shower front at different detectors enable the determination of the arrival direction and large area shielded counters record the associated muons. The mu-poor or mu-less criterion for showers preferentially select γ-ray-induced showers and help in reducing the background from the dominant hadron-induced cosmic-ray showers. While the second method has the advantage that the array can operate day and night and many sources can be observed at the same time, the first one has the disadvantage that the operation is confined only to dark moonless, cloudless nights and only one source can be observed at a time. The EAS method was first used by the BASJE group[3] who set up a specially designed array at the high altitude station in Bolivia. The Lebedev group[4] first used the ACT method at Pamir.

The two methods have undergone considerable sophistication in the last several decades. Typical modern day arrays of each type are shown in Figures 1 and 2.

It turned out that both types of experiments, having operated for several years in the early sixties, yielded negative results. Only upper limits could be set on the flux of high energy photons from supernova remnants. Chudakov *et al.*[4] set an upper limit of 5×10^{-11} photons $\text{cm}^{-2}\,\text{s}^{-1}$ for gamma rays of energy > 5 TeV, almost three orders of magnitude smaller than that suggested by Cocconi.

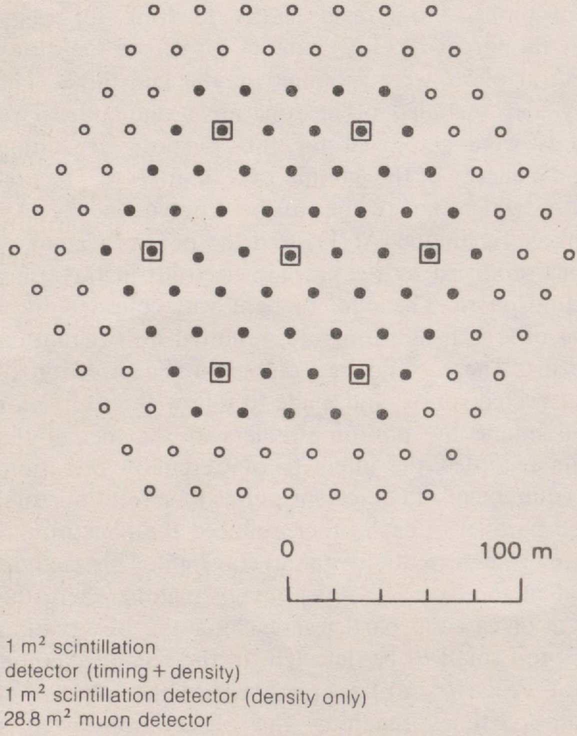

Figure 1. A typical air shower array for PeV gamma-ray observations being operated at Kolar Gold Fields (KGF), India. The total number of particles, called shower size, and hence the energy of the primary particle, are estimated from the number of shower particles recorded in the density detectors shown as open circles. The arrival direction of the shower is obtained from the relative arrival times of the shower front recorded in the timing detectors shown as filled circles. The seven muon detectors, shown as squares, sample the muon component in the shower.

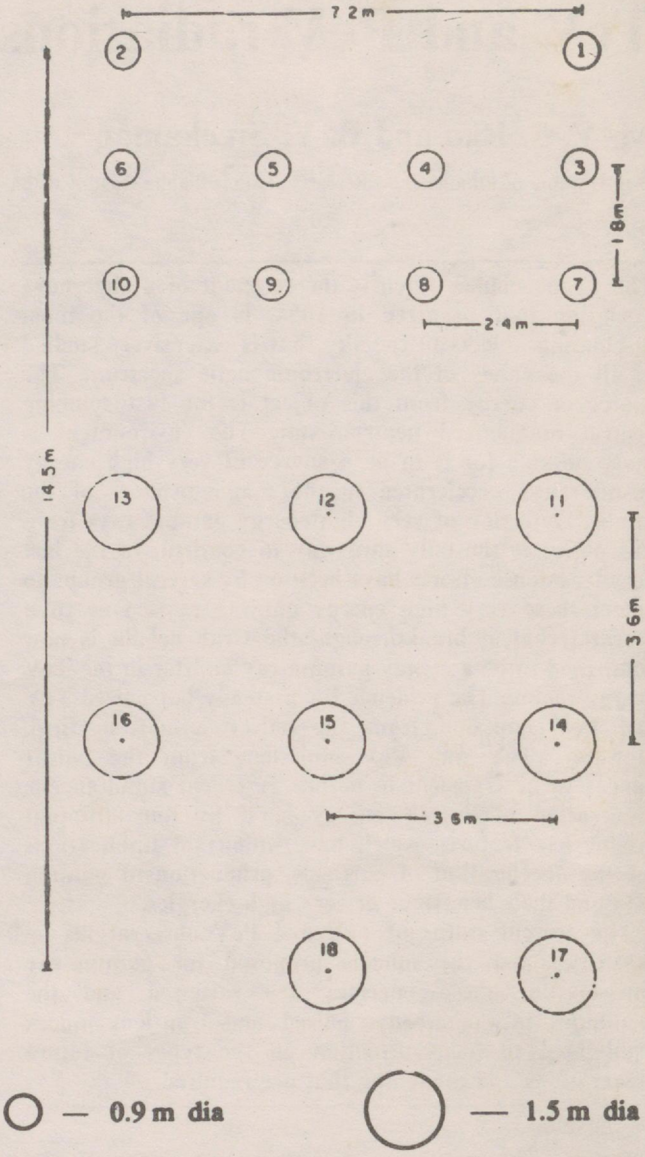

Figure 2. A typical array of parabolic mirrors for TeV gamma-ray studies at Ootacamund, India. Photomultipliers located at the foci of the mirrors collect the Cerenkov light emitted by the shower particles in the atmosphere. The night sky background is reduced by operating them in coincidence. The telescope is pointed at the source under observation with a typical aperture of about a degree. The cosmic ray background is obtained by pointing the telescope off the source, but in the same region of local zenith angle.

In 1963 a new development took place and the Crab nebula came back to the prime focus of research efforts, from which position it has not moved out, but has continued to provide many surprises of fundamental interest to both physicists and astrophysicists. While the first soft X-ray source discovered in a rocket experiment was Sco X-1, the first hard X-ray source discovered in a balloon experiment was Tau X-1, identified with the Crab nebula. The very first reaction to finding an X-ray source in the Crab was that the X-rays were coming from the neighbourhood of the neutron star that was supposed to be left behind in the supernova explosion. H. Y. Chiu indicated this possibility at the first Texas Symposium held in December 1963. However, the rocket experiment carried out by the NRL group (prompted by Schklovsky) in which the occultation of the Crab nebula by the moon was utilized for measuring the size of the X-ray source, disproved the neutron star hypothesis since the size found was much too large.

However, within a few years a major surprise was in store. In 1968 the fastest radio pulsar with a pulsation rate of 30 per second, turned out to be right in the centre of the Crab nebula and was soon identified using the stroboscopic technique for the pulsing optical signal, to be the remnant star of the supernova explosion and the neutron star hypothesis fitted all the observations. It was estimated that the spinning neutron star would be surrounded by a dipole magnetic field of $\sim 10^{12}$ G. Such a scenario was what was just necessary for the theorists to propose several possible ways in which particles could be accelerated to high energies. In these models the spinning neutron star was the central engine for energy generation and replenishment of what was being removed from the nebula in the form of radiations in the various bands of the electromagnetic spectrum. Pulsation at the rate of 30 per second was recorded in IR, optical, UV and X-ray regions and also in MeV gamma ray energy region by satellite experiments. All this led to a revival of interest in further observations on the Crab nebula in the TeV and PeV energy regions as well.

There are some excellent reviews[5-11] on the subject of TeV and PeV gamma ray astronomy, in which the Crab is covered. In this article, we review the current observational status of the high energy Crab and examine to what extent the models proposed for high energy gamma-ray production fit the experimental observations. We discuss some of the problems raised by the new observations in understanding the high energy astrophysical phenomena.

Steady TeV and PeV emission from the Crab nebula

In 1965 Gould[12] proposed that high energy electrons, whose source was not specified, would Compton scatter on the synchrotron radiation they emit in the nebular magnetic field and boost them to high energies. According to this Compton-synchrotron model, the flux of TeV energy photons was estimated to be $\sim 10^{-10}$ cm^{-2} s^{-1}, assuming an equipartition magnetic field of 10^{-4} G. This model was subsequently refined by others[13,14] using the updated parameters of the nebula.

Several groups[15-17] attempted without success to detect this flux and set only upper limits. The first positive detection of TeV energy gamma rays from the nebula was reported by Fazio *et al.*[18] (Smithsonian group) in 1972 after three years of observation. From 150 h of observations they detected a signal at 3σ level and estimated a flux of $(5.7 \pm 1.8) \times 10^{-11}$ photons cm^{-2} s^{-1} of energy above 0.14 TeV. They also presented some evidence for time variation correlated with glitches in the pulsar. Mukanov *et al.*[19] using the drift-scan method, in which the source was allowed to drift across the field of view of the telescope, at Tien Shan obtained a flux of $(5.7 \pm 1.3) \times 10^{-11}$ photons cm^{-2} s^{-1} at energy > 2 TeV.

A very important development has taken place recently in detecting steady emission of TeV gamma rays from the Crab nebula. The Whipple group[20-23], using the 'imaging' technique, developed over a period of time, to select gamma-ray-like events has succeeded in detecting a significant flux with their 10-m imaging camera. The technique makes use of the fact that the angular distribution of the Cerenkov-emitting electrons, and hence of the photons themselves, is narrower in gamma-ray cascades compared to cosmic ray background proton-induced showers. In the pure electromagnetic cascades the spread is determined only by the Coulomb scattering of the electrons in the cascade whereas in proton-induced showers the opening angles of π° mesons produced in the nuclear cascade dominate and broaden the distribution. They used the Monte Carlo simulations of gamma-ray and cosmic-ray showers developed by Hillas[24] to define a quantitative criterion (Azwidth) to differentiate gamma-ray showers from hadron showers with a high efficiency. In the early eighties, even with a crude selection of gamma-ray events with narrow Cerenkov images, they obtained a 5σ signal[20] and reported a flux of 6×10^{-11} photons cm^{-2} s^{-1} at $E > 0.4$ TeV. Later they refined this technique and reduced the cosmic-ray background by 97% using small values of the 'azwidth' parameter, which selects events not only with narrow angular width but also those arriving in the central part of the field of view. With this technique they detected[21] the source at a level of 9σ during 1986–88, which was the most significant signal from Crab at that time. These observations yielded a flux of 1.8×10^{-11} photons cm^{-2} s^{-1} at $E > 0.7$ TeV, with a factor of 1.5 uncertainty in both flux and energy estimates. They also found that the emission is constant within statistics over this period and indicated the possibility that the Crab nebula might be a 'standard candle' for TeV gamma-ray astronomy.

The Whipple collaboration have in recent years further improved their camera with a smaller pixel size, a lower energy threshold and a still better discrimination against cosmic-ray showers and have obtained a 20 σ signal during 1988–89 (ref. 23), which gave a flux of 7×10^{-11} photons $cm^{-2} s^{-1}$ at $E > 0.4$ TeV. With such a strong signal and the measured pulse height spectrum, they have been able to estimate the source energy spectrum[23]. The differential energy spectrum is found to be $N(E)\, dE = 2.5 \times 10^{-10}\, (E/0.4)^{-2.4 \pm 0.3}\, dE$ photons $cm^{-2} s^{-1} TeV^{-1}$ with E in TeV. The virtue of obtaining the energy spectrum from a single experiment cannot be overstated. It obviates the uncertainties in energy thresholds and fluxes of widely different experiments carried out in different locations and at different times. They found that the monthly average fluxes are constant over this entire period, confirming that Crab nebula is indeed a 'standard candle' in the TeV energy region.

Several other groups[25–27], using a similar technique, have also detected steady emission and confirmed the nebula to be a steady TeV source. The University of Michigan group[25] applying selection criteria, similar to the earlier crude criteria of the Whipple group, on their data collected during November–December 1988 obtained a 5.8 σ signal and gave a flux of 1.8×10^{-10} photons $cm^{-2} s^{-1}$ at $E > 0.2$ TeV. The University of California Collaboration[26,27], using a slightly different technique of pulse shape discrimination and drift-scan method, have also detected the signal at a level of 4.2 σ and reported a flux of $(2.5 \pm 1.3) \times 10^{-11}$ photons $cm^{-2} s^{-1}$ at $E > 0.6$ TeV.

In the PeV energy region, where the EAS method is used, the estimate of background is easier because the background is automatically monitored all the time. The Lodz group[28] found a 5.4 σ excess at > 10 PeV from the direction of Crab, summing up the results of a seven-year period from 1975 to 1982. Due to poor angular resolution the excess was seen over a large angular bin around Crab (37.5° in right ascension and 10° in declination); so it is not clear if all the excess is from Crab. The deduced flux was 2×10^{-13} photons $cm^{-2} s^{-1}$ at $E > 10$ PeV. The muon content of the showers from Crab was not significantly smaller than that in the cosmic-ray background showers. However, the errors on the muon measurements were such that no conclusions could be drawn about the nature of the primaries. For example, the muon content, relative to that in cosmic-ray showers, in the data sample collected during 1968–75 was found to be[29] 0.60 ± 0.12, which was consistent with both gamma-ray and proton-primary hypotheses within 3 σ. The total data sample[28] collected during 1968–82 seems to show somewhat higher muon content. The Tien Shan group[30] also detected the signal from Crab during 1974–82 with their EAS array at the Tien Shan mountain station, but only in muon-poor showers of somewhat lower primary energy. They also used a large angular bin of 15° × 15° around Crab. The fluxes reported by them are $(2.8 \pm 0.8) \times 10^{-13}$ and $(1.9 \pm 0.7) \times 10^{-13}$ photons $cm^{-2} s^{-1}$ at energies greater than 350 and 550 TeV respectively. The only other positive detection from Crab was during an episode of about six hours on 9 December 1980, reported by the Fly's eye group[31]. While they detected a 3 σ signal at $E > 1$ PeV on that day, they did not see any excess in the runs in February of the following year. The reported fluxes during the 9 December episode were $(8.2 \pm 3.1) \times 10^{-12}$, $(2.1 \pm 0.7) \times 10^{-12}$ and $(3.3 \pm 1.3) \times 10^{-13}$ photons $cm^{-2} s^{-1}$ at $E > 0.3$, 1 and 3 PeV respectively.

The Akeno group[32], however, did not find any excess at $E > 2$ PeV within 10° × 10° bin around Crab either in normal or mu-poor showers in their data collected during 1978–81. Their upper limit is an order of magnitude lower than the Lodz flux. The Haverah Park group[7] also did not find any excess in the same energy region during 1979–84. Their 95% CL upper limits are 1.5×10^{-13} and 1.5×10^{-15} photons $cm^{-2} s^{-1}$ at $E > 1$ and 10 PeV respectively. Their upper limit at 10 PeV is two orders of magnitude smaller than the finite flux reported by the Lodz group. No information on the muon content is available from this experiment.

The Durham group[33] also looked for excess in a 15° × 15° bin around Crab with their widely spread Cerenkov array at Dugway operated during 1977–80. Failing to find any excess, they set 3 σ upper limits of 1.7×10^{-13} and 6.6×10^{-14} photons $cm^{-2} s^{-1}$ at energies > 9 and 30 PeV respectively. Their limit at the lower energy is, however, consistent with the Lodz flux.

In all these PeV observations the absolute or relative time keeping was not accurate enough to subject the data for pulsar analysis. So, one cannot rule out the possibility that at least part of the emission in the reported positive detections is pulsed.

In recent years, many groups have been operating EAS arrays optimized for PeV gamma-ray observations with good angular resolution and equipped with large area muon detectors. None of them[34–39] has succeeded in detecting a finite steady flux from the Nebula.

The fluxes and the limits from the various observations over the energy range 10^{-1} to 10^{5} TeV are listed in Table 1 and plotted as a function of energy in Figure 3 and the energy spectra predicted by different theoretical models are also shown. The spectrum observed by the Whipple collaboration[23] is shown as the solid box, with the dashed lines indicating extrapolation to higher energies. The thick line marked (a) is the spectrum predicted for an ambient magnetic field of 3×10^{-4} G by the Compton-synchrotron model referred to earlier, taken from ref. 21. The recent observations, including the Whipple spectrum, based on more accurate energy and flux estimates agree very well with this model—in particular the slope of the spectrum. The disagreement with the earlier observations of the Smithsonian group[18] and the Tien Shan group[19] may

Table 1. TeV and PeV observations from Crab nebula

Ref.	Epoch	Threshold energy (TeV)	Significance (σs)	Flux (Photons cm^{-2} s^{-1})	Remarks
Positive detections					
18	1969–72	0.14	3.0	$(5.7 \pm 1.8) \times 10^{-11}$	
30	1974–82	350	4.0	$(2.8 \pm 0.8) \times 10^{-13}$	μ-poor
		550	4.2	$(1.9 \pm 0.7) \times 10^{-13}$	μ-poor
28	1975–82	10,000	5.0	2×10^{-13}	37.5° × 10°
19	1979–81	2	4.4	$(5.7 \pm 1.3) \times 10^{-11}$	
31	1980	300	2.7	$(8.2 \pm 3.1) \times 10^{-12}$	
		1,000	3.1	$(2.1 \pm 0.7) \times 10^{-12}$	
		3,000	2.5	$(3.3 \pm 1.3) \times 10^{-13}$	
20	1983–85	0.4	5.2	6×10^{-11}	
21	1986–88	0.7	9.0	1.8×10^{-11}	
26	1987	0.4 ± 0.2	4.3	$(6.3 \pm 1.5) \times 10^{-11}$	
27	1987	0.6 ± 0.3	4.2	$(2.5 \pm 1.3) \times 10^{-11}$	
25	1988–89	0.2	5.8	1.8×10^{-10}	
22	1988–89	0.4	15.3	7×10^{-11}	
23	1988–89	0.4–4.0	20.0	$(7.1 \pm 1.5) \times 10^{-11}$ $(E/0.4)^{-(1.4 \pm 0.3)}$	
Upper limits					
4	1960–63	5		5×10^{-11}	
15	1963–64	27		1.3×10^{-11}	
16	1972–75	20		2×10^{-12}	
33	1977–80	9000		1.7×10^{-13}	
		30,000		6.6×10^{-14}	
7	1979–84	1000		1.5×10^{-13}	
		10,000		1.5×10^{-15}	
31	1981	1000		5×10^{-13}	
17	1981	1		3×10^{-11}	
34	1982–84	30		10^{-11}	
38	1984–87	200		7.7×10^{-13}	
36	1987–88	45		3.9×10^{-12}	
39	1987–89	40–70		9.9×10^{-13}	
37	1988–89	150		2.2×10^{-13}	
35	1988–89	270		2.3×10^{-13}	
		600		1.8×10^{-13}	
		1200		1.3×10^{-13}	
		270		1.2×10^{-14}	μ-poor
		600		5.8×10^{-15}	μ-poor
		1200		4.5×10^{-15}	μ-poor

be due to large uncertainties in these estimates, which are truly not reflected in the error bars. This model, however, does not agree with observations in the lower 100 MeV region[24]. Cheng *et al.*[40] proposed a model in which protons accelerated up to ~ 2000 TeV in the outer magnetospheric gap of the pulsar (as in an earlier model of Cheng *et al.*[41]) are stored for a long time in the nebula due to the ambient magnetic field and these protons interact with the ambient matter in the nebula and produce π° mesons, which then decay into gamma rays. The spectrum predicted by this model is shown as curve (b) in Figure 3. While this model predicts the right magnitude of fluxes, the spectral shape does not agree. In yet another model proposed by Kwok and Cheng[42] and referred to by Vacanti *et al.*[23], the relativistic electrons accelerated in the outer magnetosphere enter the nebula and Compton-scatter on the infra red photons they themselves produce by synchrotron mechanism and boost the photons to very high energies; these photons further cascade and produce TeV gamma rays which escape and are the ones that are detected in the experiments. Perhaps a combination of all these processes is responsible for the observed fluxes and spectral characteristics.

Recently De Jager and Harding[43] recalculated the Compton-synchrotron spectrum using a more detailed magnetic field structure in the nebula. They argue that the magnetic field increases with distance, r, as the wind sweeps up the field until equipartition is reached and falls off as $1/r$ thereafter. The only free parameter in their model is σ, which decides the partition between the particle and magnetic luminosity of the pulsar. They also use an electron energy spectrum derived as a function of r from the radio, optical and X-ray observations. Their results are shown as dotted curve in Figure 3. The best fit to the TeV observations is obtained with $\sigma = 0.001$. Their model also predicts correct fluxes in the 100 MeV region, but requires electrons of energy ~ 10^{16} eV in the nebula. They suggest that TeV electrons, escaping from the pulsar,

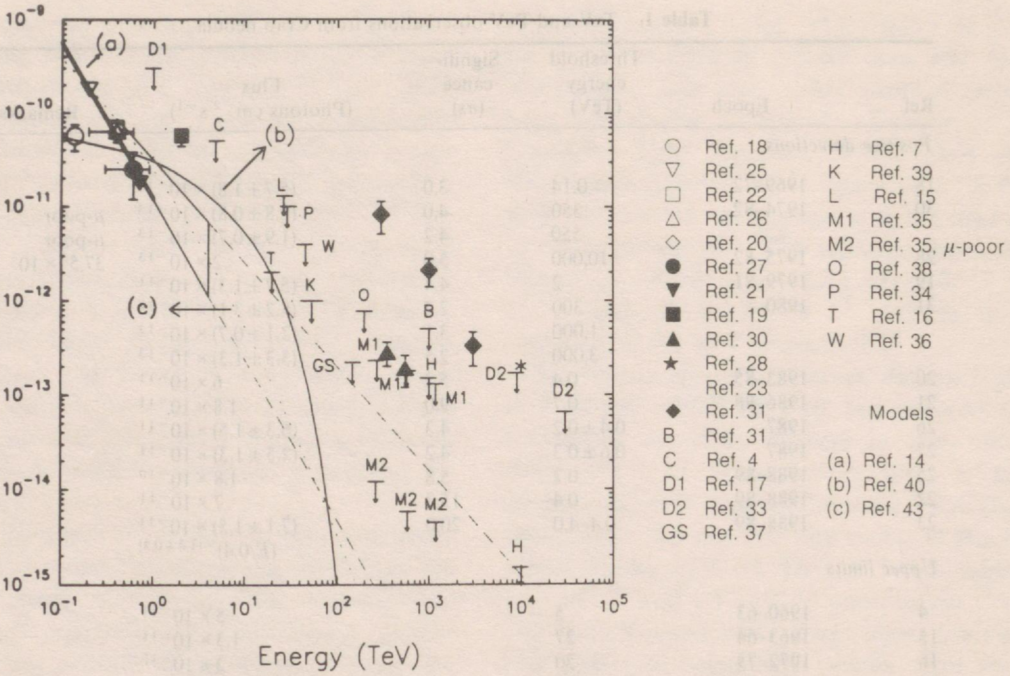

Figure 3. Energy spectrum of gamma rays from Crab nebula. The dashed lines are the extrapolations of the upper and lower 1 s limits of the observed Whipple spectrum. The thick line is the prediction of the Compton-synchrotron model of Grindlay and Hoffman[14]. The solid curve is the prediction of the hadronic model of Cheng *et al.*[40]. The dotted curve is due to the refined model of De Jager and Harding[43].

gain energy from shock acceleration in the nebula. Using the theory of parallel non-relativistic shocks, they estimate the maximum gain in energy to be 3×10^{15} eV. They suggest that observations in the PeV energy region and a spectral depression in the GeV region will give a measure of the magnetic field at the shock (smaller the field, larger the PeV flux) and the maximum gain in energy due to shock acceleration.

In the PeV energy region, all the upper limits are consistent with the extrapolation of the Whipple spectrum shown by dashed lines. The Fly's eye points (Boone *et al.*[31]) correspond to episodic emission lasting a few hours and is several orders of magnitude higher. The Tien Shan fluxes at a few hundred TeV (Kirov *et al.*[30]), based on mu-poor selection are also higher than the extrapolated spectrum. The upper limits for mu-poor showers given by the Utah–Michigan collaboration (Corbato *et al.*[35]), marked M2 in Figure 3, are however in complete disagreement with the Tien Shan results. There is no time overlap between the two experiments. Long term variability of the source on the scale of several years has to be invoked in order to reconcile these results. The most disturbing discrepancy in the PeV region is between the Lodz (Dzikowski *et al.*[28]) and the Haverah Park (Watson[7]) experiments which are contemporaneous. The finite flux of the Lodz group is about 100 times larger than the upper limit of the Haverah Park group. One way to understand the wide discrepancy is to assume that the Lodz flux is not from the Crab alone, but also forms part of general emission from the galactic plane. The Lodz group[44] found from the same data base, excess mu-poor showers within ±17.5° of the galactic plane. They constitute 1–2% of the cosmic-ray flux and so the gamma-ray flux from the galactic plane is about 2.3×10^{-14} photons cm^{-2} s^{-1} sr^{-1} at $E > 10$ PeV. Therefore the cosmic gamma-ray flux expected in the solid angle around Crab (37.5° × 10°) in the Lodz experiment is $\sim 2.6 \times 10^{-15}$ photons cm^{-2} s^{-1}, which is two orders of magnitude lower than the reported flux from Crab. The expected cosmic gamma-ray flux in the Haverah Park experiment (solid angle of 6° × 6°) is $\sim 2.5 \times 10^{-16}$ photons cm^{-2} s^{-1}, which is consistent with their upper limit of 1.5×10^{-15} photons cm^{-2} s^{-1} at $E > 10$ PeV. Thus it is difficult to understand the large flux seen in the Lodz experiment either in terms of flux from Crab or background gamma-ray flux.

The emission due to the Compton-synchrotron process does not extend to PeV energies because of severe energy losses of the electrons during acceleration. In the hadronic model of Cheng *et al.*[40] the spectrum extends beyond 10 TeV, but shows a sharp cut off around 100 TeV, even though, according to the model, protons could be accelerated up to $\sim 10^{17}$ eV in the pulsar outer magnetosphere and then confined in the nebula. This sharp cut off in the gamma-ray spectrum may be because they have used the scale-breaking model of Wdowczyk and Wolfendale[45] for hadronic interactions. In this interaction model scaling is violated in the fragmentation region also, because of which the π°s cannot acquire high enough energies. There is evidence from recent accelerator data[46], however, that scaling is preserved in the fragmentation region at PeV energies. If this feature is included in the calculations of Cheng *et al.*, then perhaps it is possible to get higher fluxes in the PeV energy region. Also, if protons can be re-accelerated in the nebula due to shock mechanism, as are electrons in the model of De Jager and Harding, higher fluxes of PeV gamma rays can be expected.

TeV and PeV pulsed emission from the Crab pulsar

Soon after the discovery of pulsars, several groups[47–51] looked for TeV pulsed emission from the Crab pulsar. While some of them reported only upper limits[47,49], the first positive detection came from Grindlay[48] of the Smithsonian group. He used a technique[52], for the first time in the TeV region, to distinguish between gamma-ray and cosmic-ray showers. He used an assembly of three mirrors to collect the Cerenkov light produced by the shower particles. Two of the mirrors, located 70 m apart, were pointed but with a slight convergence between them along the direction of the Crab such that they collected the Cerenkov light produced by the particles at the shower maximum high in the atmosphere. The third mirror, also oriented in the direction of Crab, had a larger tilt and pointed to a region lower in the atmosphere to record the Cerenkov light emitted by muons, which penetrated to deeper levels. To select gamma-ray showers the third mirror was used in anticoincidence since gamma-ray showers were expected to have very low muon content. Using this technique, Grindlay detected 3.5 σ and 5.4 σ signals in the main and interpulse regions respectively. The flux estimated from these observations was $(1.25 \pm 0.6) \times 10^{-11}$ photons cm^{-2} s^{-1} at $E > 0.68$ TeV. This is the first time that a signal has been detected from the pulsar when gamma-ray-like events are selected.

In the TeV-energy region several groups have improved the sensitivity of their telescopes in recent years, by increasing the number of mirrors, and installed accurate clocks that enable analysis of the data for pulsed emission. The availability of contemporaneous ephemeris from radio observations by the Jodrell Bank Radio Observatory has been a vital input for pulsar analysis. This is necessary, especially in the case of Crab, since the period increases continuously with time and occasional glitches that produce sudden changes occur. While many of these observations[23,53–55] have led to negative results regarding steady pulsed emission, evidence for episodic pulsed emission lasting over several minutes to several days has been accumulating slowly. Some of these episodes have shown emission at the radio main pulse and interpulse positions[56–60] and a few at other phases also[61,62]. The duration of the pulse has not been constant. Gupta *et al.*[57] observed two peaks (Figure 4,*f*) with a probability of 1.4×10^{-4} in the phasogram in the data collected at Ootacamund during 9 runs in February 1977 (but not in the runs in March), which they attribute to the main and interpulses on the basis of their separation; they did not have information on the absolute phase. The estimated flux was $(1.19 \pm 0.33) \times 10^{-11}$ photons cm^{-2} s^{-1} at $E > 0.5$ TeV. They subsequently[63] revised their energy and flux estimates to 6.4 TeV and $(8 \pm 2) \times 10^{-12}$ photons cm^{-2} s^{-1} due to the recalibration of the light collection efficiency of the mirrors.

More recent observations have shown transient emission of several minutes duration, essentially because special efforts were made to search for them only since the early eighties. The burst of 15-m duration observed by the Durham group[64] in October 1981 showed a broad pulse of width of about 0.3 in phase (Figure 4,*a*). Absolute phase was, however, not available. The estimated flux was $(2 \pm 0.3) \times 10^{-10}$ photons cm^{-2} s^{-1} at $E > 3$ TeV during the burst. The burst reported by the Tata group[59] was also of 15-m duration and has shown a narrow pulse at the position of the radio main pulse (Figure 4,*b*). They reported a flux of $(2.5 \pm 0.6) \times 10^{-10}$ photons cm^{-2} s^{-1} at $E > 1.2$ TeV during the burst. An important feature of this observation is that two telescopes tracked the Crab from locations separated by 11 km and both of them showed the signal while a third telescope adjacent to one of them but looking 8° away did not show any signal. This confirms that the signal is from the Crab and not due to any terrestrial phenomenon like lightning. Recently, another burst of similar duration and flux in the main pulse have been seen by the Tata group[65] from their Pachmarhi Observatory on 2 January 1989.

A very interesting feature has been reported by Vishwanath[60] from an analysis of the data base of the Tata group on the Crab in the TeV energy range. He divided all the data collected during the period 1979–85 into mini runs of one-minute duration each and selected those which showed large χ^2 for the phase distribution. Since χ^2 is only a measure of deviation from uniform distribution, excess events in individual mini runs can be at any phase and the resultant phasogram for the high χ^2 runs should show a uniform distribution if the parent distribution is uniform. However, he found that the distribution showed not only peaks at the main and interpulses but also some small excess in between the two pulses compared to the rest of the phase region (Figure 4,*c*). Based on these observations, he obtained a mini burst flux of $(1.6 \pm 0.3) \times 10^{-10}$ photons cm^{-2} s^{-1} at $E > 0.6$ TeV during

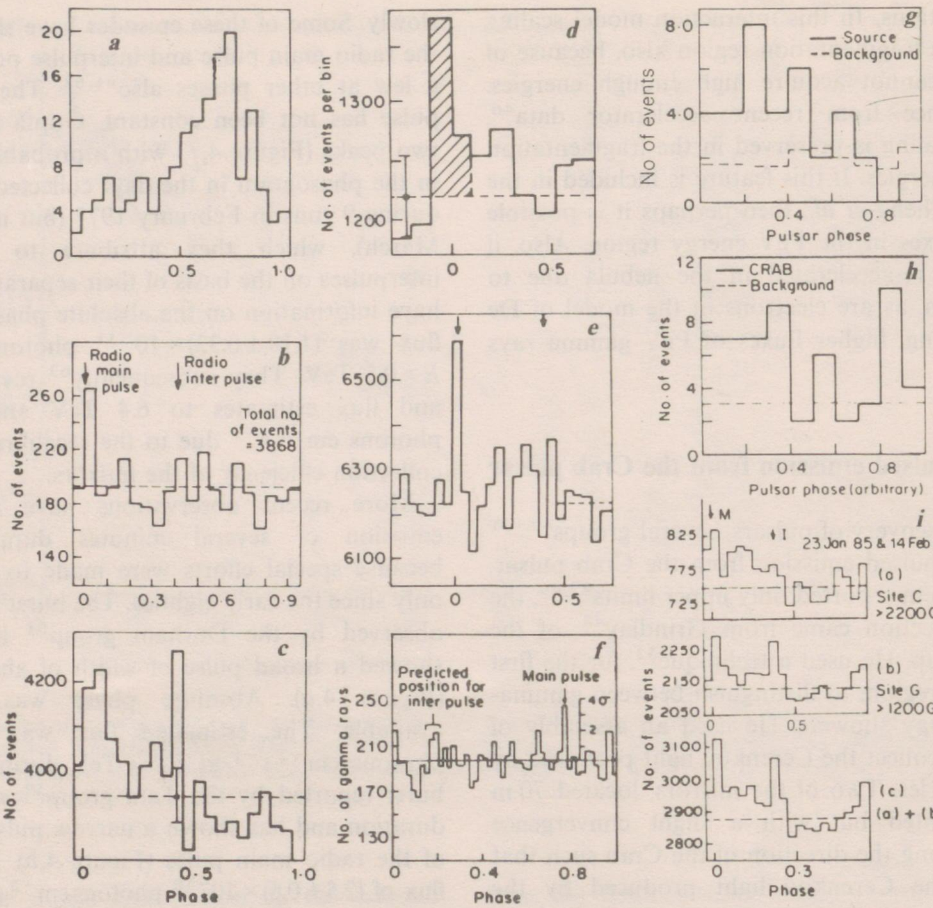

Figure 4. Light curves obtained from the Crab pulsar in various observations. They vary from narrow single, occasionally double, pulse to a broad pulse covering half the period with emission in between the main and interpulses. ***a***, Gibson *et al.*[64]; ***b***, Tumer *et al.*[58]; ***c & i***, Vishwanath[60]; ***d***, Bhat *et al.*[59]; ***e***, Dowthwaite *et al.*[66]; ***f***, Gupta *et al.*[57]; ***g***, Acharya *et al.*[78]; ***h***, Acharya *et al.*[79].

1982–83 and $(2.1 \pm 1.1) \times 10^{-11}$ photons $cm^{-2}\,s^{-1}$ at $E > 2.2$ TeV during 1984–85. Furthermore, data on two particular nights in 1985 showed a similar phase distribution (Figure 4,*i*) in the two telescopes, separated by 11 km.

The only instance of pulsed emission lasting for a long period of time was reported by the Durham group[66] during 103 h of observation from September 1982 to November 1983. The emission was confined to a narrow phase region at the radio main pulse with some weak evidence at the interpulse (Figure 4, *e*). Additional support for the genuineness of the signal was that the excess events came preferentially from the centre of the field of view identified from the relative arrival time information from well-separated detectors. They quote a probability of 6×10^{-7} for the observation to be due to chance. The detected signal constitutes $(0.233 \pm 0.054\%)$ of the cosmic-ray flux, the weakest among all reported. The resulting flux is $(7.9 \pm 1.8) \times 10^{-12}$ photons $cm^{-2}\,s^{-1}$ at $E > 1$ TeV. There was, however, no evidence for transient emission during this period. The University of California collaboration[58] also found emission at the main pulse in 22 h of observation during the two overlapping months of September and October, 1982. Their pulse width (Figure 4,*d*), however, is broader than that in the Durham observations. They found evidence that the signal enhances from 2 σ to 3.2 σ when they select showers with a broader lateral distribution of Cerenkov light. A broader lateral distribution is expected[67,68] for gamma-ray showers compared to cosmic-ray proton-induced showers. The flux reported is $(2.5 \pm 0.8) \times 10^{-11}$ photons $cm^{-2}\,s^{-1}$ at $E > 0.2$ TeV.

Recently, the Whipple collaboration[69] also reported one episode of 29-min duration at UT 04.02 on 11 January 1991 during which pulsed emission is seen at the position of the main pulse with an overall chance probability of $< 1\%$. This result was obtained with a more sophisticated selection of gamma-ray-like events, called 'supercuts', recently developed by them[70], and therefore suggests that the TeV radiation from the pulsar probably consists of gamma rays.

The light curves obtained in these various observations are shown in Figure 4. We shall discuss these results along with those in PeV energy region later.

To summarize, pulsed emission in the TeV region is mostly transient in nature though on one occasion some weak emission over a long period has been detected. The light curve seems to be highly variable, often only the main pulse is seen, occasionally both the pulses are seen and at other times a broad pulse encompassing the main and interpulses. The fluxes reported are in the region of a few times 10^{-11} photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

In the PeV region for a long time there were no reports of pulsed emission, not even upper limits, the main reason being that the clocks operating with the EAS arrays were not accurate enough to do pulsar analysis. Only recently this lacuna has been rectified in the EAS arrays. The arrays have been modified to provide good angular resolution and also equipped with large area muon detectors. The only report of pulsed emission lasting for a long period has come from the Ooty group[38]. Their phasogram, for the three year period June 1984 to May 1987, shows a 3.9 σ excess at the interpulse position. They estimate an overall chance probability of 1.6×10^{-3} of observing such an excess at any position in the phasogram. The reported flux is $(4.1 \pm 1.2) \times 10^{-13}$ photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at $E > 0.2$ PeV. They claim that the signal enhances somewhat if they select older showers (shower age > 1.4). Monte Carlo simulations by several groups[71–73], however, do not show any detectable difference in the age parameter between gamma ray and proton showers. There are no other reports of positive detection during the period 1984–87. The Los Alamos group[74] does not see any significant excess at any phase in their data collected during April 1986 to August 1989, which overlaps part of the period of the Ooty observations. They set a 90% confidence level upper limit of 6.9×10^{-14} photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at $E > 50$ TeV, which corresponds to an upper limit of 2.1×10^{-14} at $E > 200$ TeV, factor of 20 smaller than the Ooty flux. The reasons for these discrepancies are not clear.

An important development of far reaching consequence to PeV gamma-ray astronomy has recently taken place. The Baksan group[75] reported a PeV energy burst from the direction of the Crab nebula during the period 14.00–19.00 UT on 23 February 1989 with their EAS array at Baksan (atmospheric depth, 840 $\mathrm{g\,cm}^{-2}$; long. 43° E; lat. 43° N). They recorded 57 events of energy ≥ 0.2 PeV within 2°.5 of the Crab direction, corresponding to an excess of 3.9 σ (according to the likelihood ratio method of Li and Ma[76]) over the expected background of 31.1 events. The source transited at 16.5 UT. Since they searched for 333 days during 1985 and 1989 the overall chance probability for such an excess to occur was 0.02. Even though a reanalysis[77] of their data resulted in a reduced significance in the same angular bin, it is important to note that the excess still remains at a 3.1 σ (Li and Ma) significance level. This observation triggered the Tata group[78,79] to examine their data for that day only i.e. 23 February, from the EAS array operating at Kolar Gold Fields (KGF; atm. depth 920 $\mathrm{g\,cm}^{-2}$; long. 78.3° E; lat. 12.9° N). They detected the burst during the time interval 13.25–16.0 UT. The Crab transit at KGF was 14.1 UT. KGF recorded 35 events of energy ≥ 0.1 PeV against an expected background of 17.8, within an acceptance angle of 4° radius, corresponding to an excess of 3.4 σ (Li and Ma). This is the first time that what may be regarded as a simultaneous observation of PeV gamma rays has been reported from any source.

The event times were recorded in the KGF experiment with an absolute timing accuracy of ~ 1 ms. They could therefore analyse the data for pulsed emission and found that the first half of the period, which spans both the main and interpulses seen at radio frequencies, contained 26 events against an expectation of 8.9 (Figure 4, *g*). Thus all the excess events in the DC mode seem to be concentrated in the first half of the pulsar period. The significance of this result is 0.01. An analysis, by the Tata group[79], of the arrival times of the Baksan events (supplied by the Baksan group) also showed excess events in one half of the phase (Figure 4,*h*) though absolute phases were not available in this case. The significance of this result is 0.05 if the main pulse position is identified to be at phase 0.8 in this phasogram. This is the first time that pulsed emission of PeV gamma rays has been detected from Crab.

This Crab burst on 23 February 1989 has subsequently been confirmed by two more groups. The Gran Sasso collaboration[80,81], using the EASTOP array (long. 13.6° E, lat. 42.5° N), where the source transit was at 18.4 UT, detected 38 events above 0.2 PeV within an acceptance angle of 1.6° radius against an expected background of 25.5 at a significant level of 2.1 σ (Li and Ma). There is some indication that the ON source events are somewhat older than normal cosmic-ray showers. They also find an asymmetric light curve with 9 out of 13 older showers contained in one half of the period. Absolute phases were not available in this case also. An independent lower energy trigger in their experiment also showed an excess of 1.2 σ (Li and Ma).

The variation of the Crab zenith angle and the 15-min-counting rates from the three experiments are shown as function of UT in Figure 5. It is seen that the burst has lasted several hours starting at 13:15 UT or earlier and ending at 19:00 UT.

Recently Chudakov[77] has reported the results of the Tien Shan array which also show an excess of 2.4 σ (Li and Ma) from the Crab during its meridian transit at Tien Shan, which is only 3° east of KGF in longitude. The Ooty EAS experiment is in a location to detect the

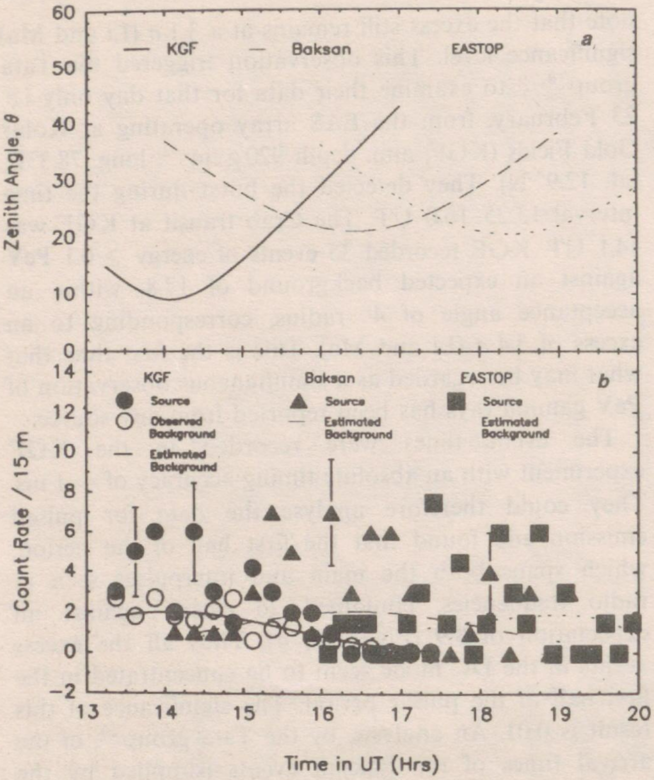

Figure 5. ***a***, Variation of the zenith angle of Crab with time on 23 February 1989 for the KGF, Baksan and EASTOP arrays. ***b***, Counting rate in 15-min intervals of events arriving from the Crab direction, plotted against Universal Time for the KGF, Baksan and EASTOP data. The background rates of cosmic rays are estimated assuming an angular distribution of Cos$^7\,\theta$ and normalized to the total expected background over the respective periods. The open circles represent the background at KGF obtained from the data itself.

burst and was in operation, but there is no report from that group as yet. Thus at least four different experiments have recorded the burst in the proper time sequence, confirming the reality of the burst. The probability that all the four groups have recorded the respective excesses from the same source on the same day purely due to chance is 6×10^{-6}. If we further consider that the KGF group has recorded a non-uniform phase distribution also, then the overall probability is 1.3×10^{-7}. Even if we take into account the reduced significance of the Baksan result and also the fact that they have extended their observations from 333 to 1256 days, this overall probability works out to be 3.5×10^{-6}.

Weekes[82] opines that the reduced excess in the Baksan result made the combined effect only marginally statistically significant and concludes that there is no strong evidence yet for emission from the Crab. The quantitative estimate of the combined probability, given above, does not corroborate his opinion and therefore his conclusion. The burst remains statistically very significant in spite of the reanalysis of the Baksan data because (i) the excess in the Baksan data on 23 February remains by itself, even after reanalysis, at a significance level of 3.1 σ; (ii) four different experiments operating at widely separated locations on the globe have recorded excess events on that day from Crab in the expected time sequence, and; (iii) the combined probability that all the four experiments have seen the excess on that day from Crab purely due to background fluctuations is 3.5×10^{-6}.

The Akeno group[83] has not seen any excess during 10–12 UT and the HEGRA group[11] also did not record any excess with their Canary Islands array, where the Crab transit time is 20.6 UT. These reports help to define roughly the starting and stopping times of the burst as indicated earlier. The temporal structure of the burst reconstructed by the Tata group[79] using the observations of the KGF, Baksan and EASTOP groups, is shown in Figure 6.

If the radiation responsible for the showers from Crab during the burst are gamma rays, then the muon content of these showers must be small compared to the normal cosmic-ray showers as discussed earlier. It is estimated from Monte Carlo simulations that gamma-ray showers should contain less than 10% of the muons in proton-initiated showers. Of the four experiments cited above, only the KGF array had muon detectors of total area of about 200 m^2 and could measure the muon content. The KGF experiment showed that showers from the direction of Crab contained nearly the same number of muons as in normal cosmic-ray background showers. The ratio of the muon content in the *excess* showers from the Crab to that in background showers was estimated to be 0.93 ± 0.34. Based on this, it could be stated that at the 95% confidence level the muon content in the *excess* showers from the Crab was greater than 37% of that in normal cosmic-ray showers. It is of importance to note here that the Kiel group[84], who first discovered Cygnus X-3 as a PeV gamma ray source, also found that the muon

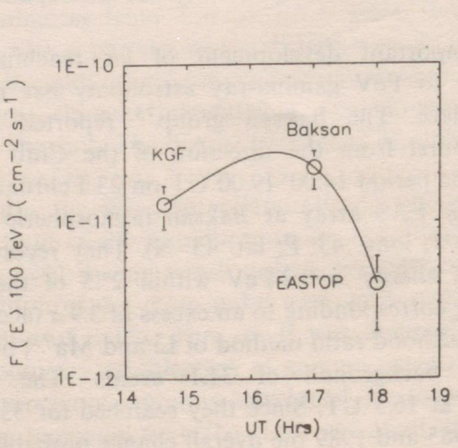

Figure 6. Variation of the excess events of energy >100 TeV from Crab with UT during the burst on 23 February 1989 from the KGF, Baksan and EASTOP experiments.

content of showers from that object also was large. The Los Alamos group[85] also report a similar finding for showers in the burst they detected from the X-ray binary source Hercules X-1. These observations regarding the muon content of the showers raise several important questions. Are gamma-ray interactions different at PeV energies compared to lower energies as suggested by some authors[86–88]? Are the primaries of these showers neutrinos which interact with almost hadronic cross-section as expected in some composite models[89]? Or is Crab emitting a hitherto unknown type of strongly interacting stable neutral particle? If the third alternative is the case then the mass of the neutral particle should be less than $40\ \mathrm{MeV\ c^{-2}}$ in order to maintain phase locking over half the Crab pulsar period. Such a low mass particle should have been detected in the accelerator experiments.

Let us now examine the features of the light curves obtained in the TeV and PeV observations of Crab shown in Figure 4. It is interesting to note that episodes lasting several hours (Figure 4, *d–i*) show in general a broad peak encompassing both the main and interpulses. While the 15-min burst reported by Gibson *et al.*[64] (Figure 4,*a*) shows a broad peak, the burst of same duration seen by Bhat *et al.*[59] (Figure 4,*b*) has a narrow main pulse. The recent burst seen on 2 January 1989 by the Pachmarhi group[65] also shows a narrow main pulse. The mini bursts reported by Vishwanath suggest, apart from the two pulses, emission in between also (Figure 4,*c*). There are also occasions when narrow main pulse or interpulse or both are seen (Figure 4, *e&f*). Thus there is ample evidence for variability of the light curve apart from the emission itself. Manchester and Taylor[90] noted a long time back that the emission in between the pulses increases with energy of the photons. This trend seems to continue to TeV and PeV energies, though quantitative estimates are not yet available. Variability of the light curve is seen at lower energies also. For example, the COS B observations[91] show that the intensity of the main and interpulses changes with time. In fact, the ratio of the intensity in the interpulse to that in the main pulse decreased with time during 1973–80. Dowthwaite *et al.*[66] also found that the ratio in the TeV energy range during 1982–83 is small and consistent with the nearest COS B observations. Ozel[92] suggested that this variation in the ratio is due to the free precession, and possibly nutation, of the pulsar with a period of 10.75 years. His fit of a sinusoidal curve to the COS B and SAS-2 dats is shown in Figure 7 along with the result of Dowthwaite *et al.* If this is the case, then combining observations over a long period of time is not a good procedure since it will not reveal the variations and also the signal will be diluted as more background is allowed in when one pulse or the other is weak. Obviously, measurement of the features of the light curve in the TeV and PeV regions with high sensitivity detectors is of utmost importance.

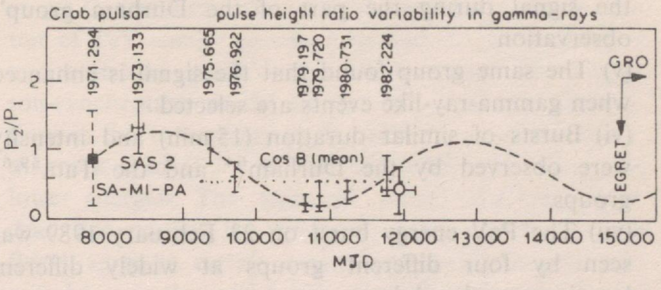

Figure 7. Dependence on time of the ratio of the intensities in the interpulse and the main pulse of COS B observations in the GeV energy region fitted to a sinusoidal curve by Ozel[92]. The observation of Dowthwaite *et al.*[66] in the TeV energy, shown as open circle, also agrees with the hypothesis that this variation is due to the precession of the neutron star with a period of 10.75 years.

It is clear that steady pulsed emission from Crab, if at all present, is very weak and perhaps just at the threshold of sensitivity of the present day detectors. The pulsed emission can be detected only when it is enhanced for short durations or when the background fluctuates on the lower side as in the case of the mini bursts reported by Vishwanath. In his analysis, 263 out of a total of 10,489 mini runs show the signal; so the time averaged flux over the entire period of observation works out to be $(4.0 \pm 0.8) \times 10^{-12}$ photons $\mathrm{cm^{-2}\ s^{-1}}$ at $E > 0.6$ TeV, which is compatible with the time averaged flux of $(7.9 \pm 1.8) \times 10^{-12}$ photons $\mathrm{cm^{-2}\ s^{-1}}$ at $E > 1$ TeV reported for the period 1982–83 by Dowthwaite *et al.*[66], considering the uncertainties in the estimates of energies and fluxes. Though Dowthwaite *et al.* mention that there is no evidence in the data for sporadic activity on time scale of minutes as strong as that reported by Gibson *et al.*[64], it is not clear whether the detected emission is due to a number of mini bursts spread over the entire observation time as in the case of the Ooty observations. It is, therefore, very important to search for such mini burst activity.

Some gamma-ray astronomers are somewhat skeptical about the episodic activity in the TeV and PeV region arguing that the episodes are not reproducible and several of them are at marginal significance. In the case of Crab pulsar, however, there are several features that suggest that at least some of the observations are not due to background fluctuations. These are:

(i) The Smithsonian group[48,62] found the signal only when they selected gamma-ray-like events

(ii) The Tata group[59,60] observed the episodes on at least two occasions at two different locations 11 km apart; they did not see any excess in the telescope looking away from Crab

(iii) The Durham group's[66] observation shows that the signal is concentrated near the direction of the source

(iv) The University of California collaboration[58] found the signal during the part of the Durham group's observation

(v) The same group found that the signal is enhanced when gamma-ray-like events are selected

(vi) Bursts of similar duration (15 min) and intensity were observed by the Durham[64] and the Tata[59,65] groups

(vii) The PeV energy burst on 23 February 1989 was seen by four different groups at widely different locations on the globe.

Thus TeV and PeV emission from the pulsar appears to be sporadic in nature and future efforts should be concentrated on detecting these with coordinated observations by several groups.

The fluxes and upper limits reported in the various observations are listed in Table 2 and shown in Figure 8 and compared with theoretical models.

Theoretical models for TeV and PeV gamma-ray emission from pulsars are not yet well developed, perhaps because the observations are not yet on a firm statistical footing. In the lower energy region, however, some models have been put forward to explain the light curve as well as the energy spectrum. Cheng *et al.*[41] proposed a model in which electrons and positrons are accelerated in the outer gap in the magnetosphere of an obliquely rotating pulsar, where large electric fields can be sustained. These particles generate photons due to various electromagnetic processes, which in turn create $e^{\pm}$ pairs. The pulsed low-energy gamma rays are a result of synchrotron radiation from these $e^{\pm}$ pairs. Up to a few GeV the predictions of the model on light curve and spectra agree with observations on Crab as well as Vela pulsars. A small fraction of the $e^{\pm}$ is lost by inverse Compton scattering on the soft photons, which are boosted to a few TeV. In Crab, these photons are absorbed by the soft photons and create $e^{\pm}$, which synchrotron radiate with a characteristic energy of ~ TeV. However, the authors argue that these gamma

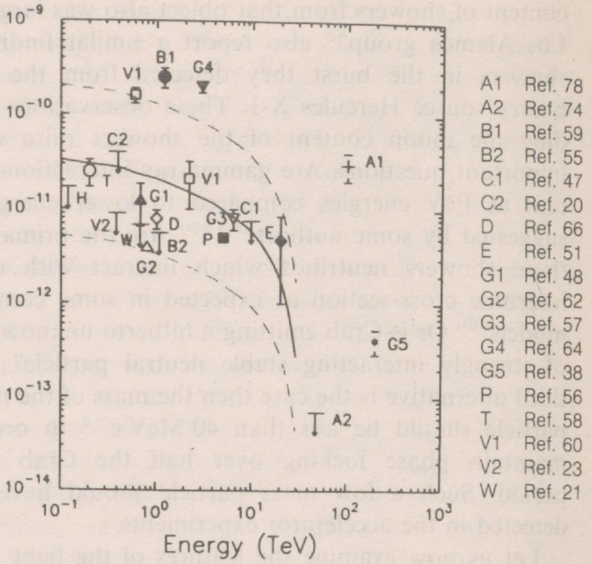

Figure 8. Energy spectrum of gamma rays from the Crab pulsar. The solid curve is the prediction of the model of Bogovalov and Kotov[94]. The dashed curves are the result of fluctuations in the product $T\lambda$ by a factor of 2.5 on either side, estimated by us. The points marked B1, G4 and V1, which are due to transients, are interpreted as due to temporal variations in this parameter.

Table 2. TeV and PeV observations from Crab pulsar

Ref.	Epoch	Threshold energy (TeV)	Significance (σs)	Flux (photons cm^{-2} s^{-1})	Remarks
Positive detections					
48	1971	0.68		$(1.3 \pm 0.6) \times 10^{-11}$	
56	1972–73	5.0		5×10^{-12}	
62	1973	0.8	5.1	4×10^{-12}	
51	1975	20.0		$(4.7^{+5.5}_{-3.7}) \times 10^{-12}$	
57	Feb, 1977	0.5	3.6	$(1.2 \pm 0.3) \times 10^{-11}$	
64	23 Oct 1981	3.0		$(2 \pm 0.3) \times 10^{-10}$	
66	1982–83	1.0		$(7.9 \pm 1.8) \times 10^{-12}$	
58	Sep–Oct. 1982	0.2	3.2	$(2.5 \pm 0.8) \times 10^{-11}$	
60	1982–83	0.6		$(1.6 \pm 0.3) \times 10^{-10}$	
	1984–85	2.2		$(2.1 \pm 1.1) \times 10^{-11}$	
19	23 Jan. 1985	1.2	5.1	$(2.5 \pm 0.6) \times 10^{-10}$	
38	1984–87	200.0	3.9	$(4.1 \pm 1.2) \times 10^{-13}$	
75	23 Feb. 1989	200.0	3.9	$(1.1 \pm 0.3) \times 10^{-11}$	
78	23 Feb. 1989	100.0	3.9	$(1.3 \pm 0.4) \times 10^{-11}$	
80	23 Feb. 1989	200.0	2.1	$(2 \pm 1) \times 10^{-12}$	
Upper limits					
47	1969–70	10.0		7.5×10^{-12}	
20	1983–84	0.4		1.1×10^{-11}	
21	1986–88	0.7		6.8×10^{-12}	
74	1986–89	50.0		6.9×10^{-14}	
55	1988–89	1.1		5.6×10^{-12}	
23	1988–89	0.4		7×10^{-12}	

rays may not be able to escape further absorption in the magnetosphere itself, except when density fluctuations occur in the secondary flows. They predict only a single pulse in the light curve because the inward-moving TeV gamma rays pass through strong magnetic fields and are absorbed by pair creation. The observations, however, show that both pulses as well as a broad pulse are seen often. Also, there is no prediction of the energy spectrum in the TeV region.

Bogovalov[93] suggested that in an aligned rotator, a rotational discontinuity could be formed in the flow of the plasma near the light cylinder, and particles are accelerated in this discontinuous region to TeV energies, deriving energy from the azimuthal magnetic field generated by the rotating neutron star. These particles then produce the TeV gamma rays by the inverse Compton scattering on the thermal photons emitted by the neutron star. The gamma rays can easily escape and be detected as they are produced near the light cylinder. Bogovalov and Kotov[94] calculated the energy spectrum of the gamma rays in this model. Their spectrum is shown in Figure 8. In their model, the flux is proportional to $T^2\lambda^2$, where T and λ are the surface temperature of the neutron star in K and the plasma density in units of the Goldreich density respectively. Their result for $T = 10^6$ K and $\lambda = 10^3$ is shown as the full curve in the figure. The dashed lines are drawn by us for a factor of 2.5 variation in $T\lambda$, commensurate with the upper limit of 2.5×10^6 K for the surface temperature derived by Harnden and Seward[95]. It is seen that almost all the observations agree with this model, except the burst events in the TeV region marked B1, G4 and V1 of references 59, 64, and 60 respectively. These are suggested to be due to sudden increases in the surface temperature, perhaps, during starquakes. The two points from Vishwanath[60] marked V1 at 0.6 TeV and 2.2 TeV correspond to different periods of time separated by two years. The widely different intensities may be due to different values of $T\lambda$. Bogovalov and Kotov, however, have not calculated the light curve. The long term flux of the Ooty group[38] and the seven-hour burst seen by the KGF and other groups[77–81] are not reproduced in this model since there is sharp cut off at a few tens of TeV. To explain these, one may have to consider acceleration of protons to PeV energies and subsequent photo–nuclear interactions with the ambient photons and production of π°s, which, then decay into gamma rays. Cheng *et al.*[41] consider briefly such a possibility within the light cylinder, but conclude that the gamma rays cannot escape creation of Sturrock pairs in the local magnetic field. The proton acceleration process may, however, just be possible in the Bogovalov–Kotov model.

Summary

The Azwidth method employed by the Whipple group seems to establish that the Crab nebula is a steady emitter of TeV energy gamma rays and can be considered as a 'standard candle' in this energy region. The Compton-synchrotron model agrees well with the observations in the TeV energy region with an ambient nebular magnetic field of 3×10^{-4} G, though it seems to fail at lower energies. The 'hadronic' model of Cheng *et al.* does not predict the spectrum correctly, though the fluxes agree in certain energy regions. Both processes may be operative and further observations over a wider energy range with more accurate estimates of energies and fluxes are needed to establish the energy spectrum on a firm basis. The PeV observations are difficult to understand in any of these models. If the appropriate hadron interaction model is incorporated in Cheng *et al.*'s model, better agreement can perhaps be obtained. The muon content in the PeV energy region, however, remains an enigma.

The light curves in the TeV as well as the PeV region seem to be variable with either the main or the interpulse or both being seen as narrow pulses some times, while a broad pulse encompassing both is seen at other times. The fluxes are in general agreement with the model of Bogovalov and Kotov. The transients may be interpreted as due to temporal increase in the surface temperature due to starquakes. To explain PeV observations, further modification of this model is required. The PeV energy burst from Crab, lasting for about seven hours, seen by four different groups is of high statistical significance. The muon content registered by the KGF group in this event as well as in some of the burst events from Cyg X-3 and Her X-1 reported by other groups pose new questions regarding the nature of the particles responsible for such bursts and their interaction characteristics at high energies. A worldwide cooperative effort leading to simultaneous and sequential observation of rare burst events and their detailed characteristics is of utmost importance in this field of TeV–PeV astronomy which, in addition to astronomical aspects of significance, holds the promise of solving the problem of cosmic-ray generation and also of revealing newer aspects of particle physics at super high energies.

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Cosmic Ray Bounds on Violation of Lorentz Invariance

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Abstract

Recently Coleman and Glashow [Coleman and Glashow 1997] have developed a model which allows the introduction of a small violation of Lorentz invariance. Observational signatures arise because this interaction also violates flavor conservation and allows the radiative decay of the muon, $\mu \rightarrow e + \gamma$, whose branching ratio increases as b γ^4 where γ is the Lorentz factor of the muon with respect to the reference frame in which the dipole anisotropy of the universal microwave radiation vanishes. In this paper we place a bound on the Lorentz invariance violating parameter,b, of b$< 10^{-25}$ based on observations of horizontal air showers with $n_e \geq 5 \times 10^6$. Similar considerations of cosmic ray neutrinos in the atmosphere improve these bounds by twenty orders of magnitude.

To test by experiments the limits of validity of Lorentz invariance or indeed any of the fundamental principles of physics we need a theoretical model which assumes a specific form for the violation and makes predictions of physical phenomena which can be searched for by the experiments [Will 1993, Haugan and Will 1987, Fishbach et al 1985, Greene et al 1991]. The recent model of Coleman and Glashow incorporates tiny departures from Lorentz invariance which does not respect flavor conservation also [Coleman and Glashow 1997].

One of the signatures of such a flavor non conservation is the transition $\mu \rightarrow e + \gamma$ whose rate increases rapidly with the energy of the muon as measured in a preferred frame such as the one in which the 2.7^{o}K universal microwave background does not have any dipole anisotropy. Following their suggestion we calculate the possible contributions of such a process to the flux of "horizontal air showers" and μ-less showers which provide useful estimates for the possible strength of such an interaction and also provide a good bound on such violations[Cowsik, Sreekantan 1999]. We now extend the model to neutrinos and calculate the bound on $b_{\nu\gamma}/\tau_{\nu\gamma}$ based on the decay scheme $\nu_\mu \rightarrow \nu_e + \gamma$.

The idea on which the bound on flavor violating interactions is derived becomes clear by noting that the primary cosmic rays consist mainly of nuclei which interact strongly when they are incident on the top of the earth's atmosphere. The amount of shielding provided by the atmosphere in the vertical direction above the earth is about 1000 g cm^{-2} and increases as the secant of the zenith angle θ upto $\sim 80^o$. The total grammage in the horizontal direction is about 36500 g cm^{-2}. The primary cosmic rays interact in the atmosphere and create a 'nuclear active' cascade. Since the atmosphere is tenuous with a scale height h $\approx 7 \times 10^5$ cm, pions and kaons in the cascade decay producing the cosmic-ray muonic and neutrino component. Nuclear interactions of pions and kaons with the atmosphere compete with their decay and become increasingly dominant as the particle energy increases, so that the spectrum of the muonic and neutrino component at high energies is steeper than that of the nuclear active component by a factor E^{-1}. Also the muonic and neutrino components at high energies increases as $\sim sec\theta$, as the scale height of the atmosphere also has this dependence. Since the interaction mean free path of the hadronic components is $\sim$ 70 g cm^{-2}, after reaching their maximum development, they are absorbed with an absorption mean free path of $\sim$ 100 g cm^{-2}. In contrast the muons and neutrinos suffer only fewer interactions and propagate with hardly any reduction in flux. Now note that as we move away from the vertical towards the horizontal direction, with increasing sec θ the nuclear active components get severely absorbed but the high energy penetrating component increases as $\sim$ sec θ! Thus at large angles we have a nearly pure beam of high energy muons and neutrinos, traversing distances of the order of few times the scale height $h_\theta \sim hsec\theta$. Now should the muons and neutrino decay radiatively, the decay products will induce an electromagnetic cascade which can easily be observed signalling the violation of flavor conservation, as described in the model of Glashow and Coleman. Indeed as the energy of the penetrating component increases the observability of the cascade increases as it penetrates deeper, spreads wider and produces more observable electrons and photons. The electromagnetic cascade has a very broad peak at about 500 g cm $^{-2}$ from the point of initiation for an electron or γ of energy E $\sim 10^4$ GeV and the depth of the maximum increases logarithmically with energy. The total number of electrons at the peak of an electromagnetic cascade is approximately equal to the energy of the initiating electron or gamma ray in GeV units. Thus any array of particle detectors deployed to detect extensive air showers will be able to detect such showers generated by the radiative decay of the muon and neutrinos. There will be negligible amount of nuclear active particles and muons in these showers. The background due to showers induced by the primary cosmic ray nuclei become negligible as we go to large zenith angles. Thus 'μ-less' showers appearing in near horizontal directions constitute a signal of the new process described by Coleman and Glashow.

To quantify these ideas first consider the decay of muons into electrons and photons. We note that the spectrum of muons at high energies near the earth may be parametrized as

$$\begin{aligned} \mu(E) &= \frac{\kappa_i sec\theta}{E^{\beta_i+1}} cm^{-2}s^{-1}sr^{-1}GeV^{-1} && (1) \\ &\quad \text{with} \\ \kappa_1 &= 10, \beta_1 = 2.7 \;\; for \;\; 10^3 GeV < E < 10^5 \;\; GeV && (2) \\ &\quad \text{and} \\ \kappa_2 &= 10^4, \beta_2 = 3.3 \;\; for \;\; 10^5 GeV < E < 3 \times 10^7 GeV && (3) \end{aligned}$$

Here β_1 and β_2 are the power law exponents of the primary cosmic ray spectrum at energies of 10 to 30 times the energy of the muon.

According to Coleman and Glashow[1] the total decay probability per unit time, Γ, of a muon of Lorentz factor γ is given by:

$$\Gamma = \Gamma_w + \Gamma_r = \frac{1 + b\gamma^4}{\gamma\tau_o} = \frac{1}{\gamma\tau_o} + \frac{b\gamma^3}{\tau_o} \qquad (4)$$

Here $\tau_o \approx 2.2 \times 10^{-6}s$ is the life-time of the muon and b is a very small parameter describing the violation of Lorentz invariance and flavor conservation. For a muon to decay close to the earth, say at a distance d of about 5 km ($\sim 700gcm^{-2}$) from the air shower array, it has to survive decay during its flight though the atmosphere upto this point i.e. a distance of few times h_θ, the scale height in that direction. Thus the number of muons decaying in the 5 km stretch is given by

$$s(E) \approx \kappa sec\theta E^{-\beta-1} exp\{-jh_\theta\Gamma/c\}\,\Gamma d/c \qquad (5)$$

where j is a number of the order of 2 to 3. Noting that Γ is a small number and that at high energies $\Gamma \sim \Gamma_r$, the exponential in eq. 5 may be set to unity and eq. 5 is rewritten as

$$\begin{aligned} s(E) \sim \kappa sec\theta E^{-\beta-1}.\Gamma_r d/c &\approx \frac{\kappa sec\theta b d m_\mu^{-3}}{c\tau_o} E^{2-\beta} && (6) \\ &\equiv \kappa b\eta \, E^{2-\beta} \end{aligned}$$

where $\eta = dm_\mu^{-3}sec\theta/c\tau_o \; GeV^{-3} \approx 5 \times 10^4 \; GeV^{-3}$, for $\langle sec\theta\rangle \approx 7$. The products of the radiative decay of the muon generate an extensive air shower which contains a large number of electrons,n_e, near the maximum, related to the muon energy through the simple relation

$$n_e \approx E/\epsilon \qquad (7)$$

where $\epsilon \approx 1$ GeV for an electromagnetic shower of primary energy in the range 10^4 GeV - 10^6 GeV. The number spectrum of particles that will be seen by an air shower array is given by

$$f(n_e) \approx \epsilon^{3-\beta}.\kappa b\eta\, n_e^{2-\beta} \tag{8}$$

Or the number of showers F, of size larger than n_e is given by

$$\begin{aligned} F(n_e) &= \int_{n_e}^{\infty} f(n'_e)dn'_e && (9)\\ F_2(n_e) &= \frac{\epsilon^{3-\beta_2}\kappa_2 b\eta}{\beta_2-3} n_e^{3-\beta_2} \quad for\, n_e \geq 10^5 && (10)\\ F_1(n_e) &= \frac{\epsilon^{3-\beta_1}\kappa_1 b\eta}{3-\beta_1}\left[10^{5(3-\beta_1)} - n_e^{3-\beta_1}\right] + F_2(10^5) \quad for\ n_e < 10^5 && (11) \end{aligned}$$

We compare the integral number spectrum of horizontal air showers obtained by Nagano et al [Nagano et al 1986] with the Akeno array in Fig. 1 for $b = 10^{-23}$ and $b = 10^{-25}$. The theoretically derived spectrum is very flat, $\sim n_e^{-0.3}$, in contrast with the observed spectrum of horizontal air showers which shows $\sim n_e^{-2}$ behavior. Note that $b \sim 3 \times 10^{-23}$ is excluded even by the lower energy data at $n_e \sim 10^5$ and that the bound $b < 10^{-25}$ is obtained when we consider the fluxes of horizontal air showers quoted by Nagano et al for $n_e \sim 5 \times 10^6$. Clearly these bounds are considerably more stringent than those derived by looking at the depth intensity curves for muons and as such small values of branching ratio for radiative decay will not have any detrimental effects on the functioning of muon colliders (Coleman and Glashow 1998). It is interesting to note that in the Coleman Glashow model this limit translates to $\mid 1 - c \mid \leq 6 \times 10^{-21}$

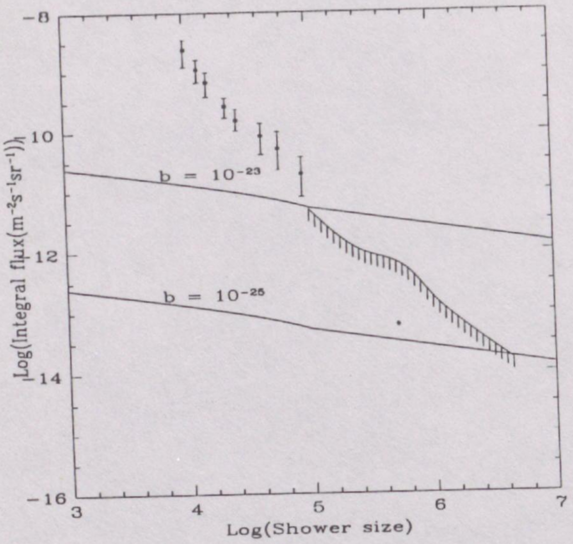

Figure 1: *The integral flux of horizontal air showers given by Nagano et al. is compared with the expectation from the Coleman-Glashow process for the two values of b,* 10^{-23} *and* 10^{-25} *respectively.*

Now, let us suppose that the radiative decay process for the muon suggested by Coleman and Glashow is also applicable to the neutrinos leading to the decay scheme: $\nu_\mu \rightarrow \nu_e + \gamma$, then the horizontal showers may be used to set a strict bound on this process as well. The calculations of the high-energy cosmic-ray neutrino fluxes in the near horizontal direction (Cowsik et al. 1966, Gaisser et al. 1988, Volkova 1980, Volkova and Zatespin 1983) may be approximated to a single power law

$$\nu_\mu(E) \approx \frac{\kappa_\nu \sec\theta}{E^{\beta_\nu+1}} \qquad cm^2\, sec^{-1}\, sr^{-1}\, GeV^{-1} \tag{12}$$

for $10^3 GeV < E_\nu < 10^6 GeV$, with $\kappa_\nu \approx 10$ and $\beta_\nu = 3$. As before its decay according to the equations (14) and (4), leads to a horizontal air shower flux,

$$F_\nu(n_e) = \frac{\epsilon^{3-\beta_\nu}\kappa_\nu \sec\theta d}{(3-\beta_\nu)c}\, \frac{b_{\nu\gamma}}{\tau_{\nu\gamma}} \left(\frac{2m_2^2}{m_2^2 - m_1^2}\right)^{3-\beta_\nu} \frac{1}{m_2^2} n_e^{3-\beta_\nu} \tag{13}$$

where m_2 is the mass of the muon neutrino, m_1 is the mass of the electron neutrino, $b_{\nu\gamma}$ is the branching ratio and $\tau_{\nu\gamma}$ the life time for the process given in equation (14). Notice that equation (16) is weakly sensitive to

$\Delta m^2 = m_2^2 - m_1^2$ and highly sensitive to m_2. Comparison with the data on horizontal showers as in figure 1 yields the following strict bound for $b_{\nu\gamma}/\tau_{\nu\gamma}$,

Table 1:
Bound on $b_{\nu\gamma}/\tau_{\nu\gamma}$ for various values of Δm^2 and m_2 obtained by camparing the expected integral flux from Caloman-Glashow process with the integral spectrum given Nogano et al. as in Fig. 1.

Δm^2 (eV^2)	m_2 (eV)	bound on $b_{\nu\gamma}/\tau_{\nu\gamma}(sec^{-1})$
10^{-5}	10^{-2}	1×10^{-47}
10^{-5}	10^{-1}	3×10^{-44}
10^{-5}	1	1×10^{-40}
10^{-5}	10	4×10^{-37}
10^{-3}	10^{-2}	1×10^{-48}
10^{-3}	10^{-1}	1×10^{-44}
10^{-3}	1	3×10^{-41}
10^{-3}	10	1×10^{-37}
10^{-2}	10^{-2}	1×10^{-48}
10^{-2}	10^{-1}	5×10^{-45}
10^{-2}	1	1×10^{-41}
10^{-2}	10	5×10^{-38}
1	10^{-2}	3×10^{-48}
1	10^{-1}	1×10^{-45}
1	1	5×10^{-42}
1	10	1×10^{-38}

If we assume $b_{\nu\gamma}$ to be one, this will yield $\tau_{\nu\gamma} \sim 10^{41}$s!

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