J. Astrophys. Astr. (1987) **8,** 69–78

Very High Energy Gamma Rays from the Crab Pulsar

P. R. Vishwanath *Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400005*

Received 1986 July 29; accepted 1986 December 11

Abstract. The Ooty data on VHE (> 600 GeV) γ-rays from the Crab pulsar have been used to look at possible emission on three different timescales, *viz.* years, minutes and hours. When averaged over three years of observation, there is no significant time-averaged emission. But interesting aspects are revealed when the data are subdivided into miniruns of one-minute duration. Minutes with moderate γ-ray activity were isolated with a χ^2 analysis. The summed phasogram of such minutes shows two strong peaks coinciding with the radio main pulse and the interpulse respectively. The probability that these are due to chance is small. The phasogram has a bimodal distribution which indicates some emission from the middle region between the two phases. In general, there is no significant emission on the timescale of a few hours. However, the main pulse, as well as the bimodal distribution, were seen also in the total data of two nights of simultaneous observation at two sites during 1984–1985.

Key words: γ-ray astronomy—pulsars, VHE γ–rays—Crab pulsar

1. Introduction

Observations with ground-based atmospheric Cerenkov technique have been on since 1969 for the detection of very high energy (VHE) γ-rays from the Crab pulsar. In recent years, two types of emission from the pulsar have been reported. The first is a weak (~ 4σ) time-averaged emission: a signal aligned with the radio main pulse was seen (a) in 1983–1984 by the University of Durham group (Dowthwaite *et al.* 1984), and (b) in 1984 by the Iowa State University–JPL collaboration (Turner *et al.* 1985). The other type of emission, stronger (> 5σ) and short-lived (15 minutes), was seen (a) in 1983 October by the University of Durham group (Gibson *et al.* 1984), and (b) in 1985 January by the Tata Institute of Fundamental Research (TIFR) group (Bhat *et al.* 1986). The phase of the signal seen by the TIFR group agreed with that of the radio main pulse, whereas there was no absolute phase information for the burst seen by the University of Durham group. Thus, according to the available information, the Crab pulsar is a steady emitter of weak flux of γ-rays and a very infrequent emitter of large bursts. In this paper, we explore the possibility of emission on three different timescales, *viz.,* years, minutes and hours. At first, we put together all data available from the TIFR observations for which absolute phase is available, in order to see whether there is any time-averaged emission. Later, we ask the question whether there is any phenomenon which is different in timescale and intensity from either the time-averaged emission or the 15-min emission. Thus, we explore the possibility of γ-ray emission in a scenario different from those explored till now.

2. The time-averaged emission

The atmospheric Cerenkov array at Ooty, described elsewhere in detail (Gupta *et al.* 1985), was used with all the mirrors close to each other in 1979–1980 and 1982–1983. In 1984–1985, the array was split up with 8 large mirrors at site G and 10 small mirrors at site C, separated from site G by 11 km (Bhat *et al*). The four data sets—1979–1980, 1982–1983, 1984–1985 (C), and 1984–1985 (G) (referred to hereafter as I, II, III and IV observations)—had energy thresholds of 3000, 600, 2200 and 800 GeV with exposures of 70.6,45.8,31.8 and 26.6 hours respectively. The phasograms for all the four data sets were obtained in the standard manner as described in earlier papers of the Ooty group (for *e.g.* Bhat *et al.*). Because we have absolute phase for all the four data sets, these data can be summed in phase. Fig. l(a) shows the total time-averaged phasogram for 174.8 hours. There is no dominant peak (> 3 σ) in the phasogram. Therefore, we derive an upper limit of 4.6×10^{-12} cm^{-2} $s^{-1}$for the time-averaged emission from the Crab

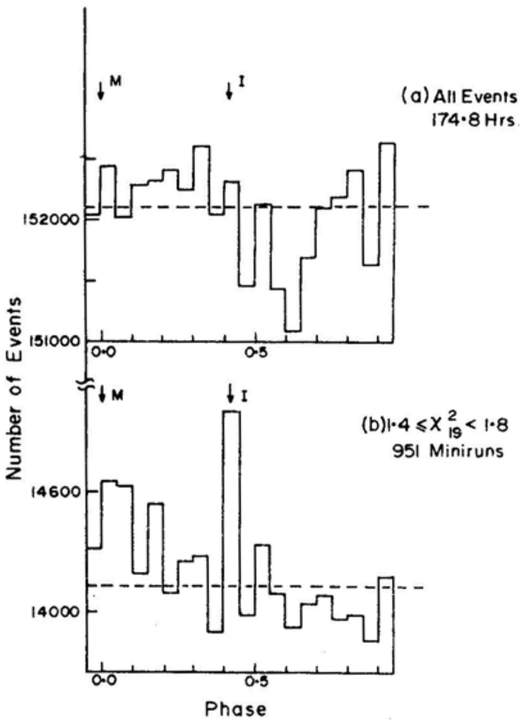

Figure 1. (a) The total phasogram of all the data sets with absolute phase. The dashed line represents the average of all the events in the phasogram. M and I refer to the position of the radio main pulse and interpulse respectively, (b) The summed phasogram of miniruns with $1.4 < \chi^2_{19} \leqslant 1.8$. The dashed line shows the average of the phasogram after substracting the events in the main and the interpulse region. Phase region 0.950–0.45 is called the region A and the remaining region is called the region B.

pulsar. This limit is not in disagreement with the flux seen by Dowthwaite *et al.* However, three of the above four data sets do show independently a very weak peak (~ 1.5 σ) at the position of the radio main pulse. Data sets I, III and IV together give a peak of 2.3 σ at the radio main pulse phase, while no other bin shows such excess. But the data set II (1982–1983), which is at the lowest threshold energy did not show any excess.

3. Emission on the timescales of minutes

We have already noted in the introduction that strong emission on timescales of 15 min has been found by two groups. The traditional way to look for such a signal is to group the data into relevant timescales and see whether there is a large excess in any bin in the phasograms (*e.g.* Bhat *et al.*). Another method was reported in an earlier paper (Vishwanath 1982) where we had shown the possibility of occasional VHE γ-ray emission in the intervals of minutes. In that analysis, we had considered positive deviation of any bin in the phasograms over timescales of minutes, but we did not have absolute phase information for that data. Both these methods have shortcomings. In the first method, the signal has to be well above the background and if there is less intense emission it would not be noted. The second method does not consider negative deviations. Negative deviations may be interesting since low-level signals could be revealed when the cosmic ray background has statistically downward fluctuation. The new analysis is based on the assumption that the signal, if present, may show up in phasograms with moderate to high χ^2 . While such a χ^2 can also be due to upward or downward statistical fluctuation of one or more bins, the total fluctuation in the signal region may be due to both statistics and presence of a signal, whereas in the background region it will be due only to statistics. The method adopted here will be to group the miniruns over minutes according to their, χ^2 values. The resultant χ^2 of the group phasogram is expected to have a large value if the deviations are not entirely due to statistics. Thus there is a possibility of a signal only in a group phasogram having a large χ^2. We should note here that in the low-energy γ-ray observations of the Cos-B group, no emission was seen in one-half of the phase plot (Wills *et al.* 1982). This possibility exists in the VHE γ-ray region also. (In fact, the excess seen by Dowthwaite *et al.* is above the mean of those bins in the phase region 0.48–0.96.) While the initial selection would be done with the 20-bin phasograms, it is interesting to use only 2 bins if the group phasogram shows a large difference between two halves of the phasogram. While χ^2_{19} (19 degree of freedom) criterion highlights individual bins with signal if there are any, χ^2_1 (1 degree of freedom) reveals whether the two phase regions have real differences. The timescale we consider here is of minutes since the earlier analysis showed the possibility of emission with this timescale.

To find whether such emissions over timescales of minutes exist, the present data were divided into miniruns of one-minute duration and phasogram for each minirun was obtained. The total number of miniruns was 10489 and the average rate per minirun was 289. χ^2 was computed for each minirun and divided by 19 to get χ^2_{19} , the reduced chi-square. Each minirun was grouped as to its χ^2_{19} . Fifteen groups were tried for χ^2_{19} *viz.* 1.0–1.1, 1.0–1.2, 1.0–1.3, 1.0–1.4, 1.0–1.6, 1.0–1.8, 1.0–1.4, 1.4–1.8, 1.2–1.6, 1.6–2.0, 1.3–1.6,1.6–1.9, > 1.8, > 1.9, and > 2.0. The group with 1.4 < χ^2_{19} 1.8 had the highest resultant χ^2_{19} of 2.7. The highest grouping viz., > 1.8, > 1.9 and > 2.0 had resultant χ^2_{19} of 1.8, 1.5 and 1.5 respectively. The phasogram for the group $1.4 < \chi^2_{19} \leqslant 1.8$ is shown in Fig. 1 (b). The expected number of miniruns in this χ^2_{19} group was 1016 whereas the observed number is 951. Both the main and the interpulses are quite prominent, whereas the bins in phase region 0.45–0.95 have, in general, lower number of events. When we divide the phasogram into two regions—region A (phase 0.95–0.45), and region B (phase 0.45–0.95)—and apply Wilcoxon's rank test (Frodesen, Skeggestad & Tofte 1980), we find the probability that the events in the two regions stem from the same population is lower than 1 per cent. There are several disparities between regions A and B. The mean rates for regions A and B in this selected group are 152.0 ± 0.4 and 149.6 ±0.4 per minirun. If we demand that the region have at least *n* (any *n*) bins showing positive excess in a minirun, 55, 28 and 8 per cent in region A and 49, 22 and 4 per cent in region B satisfy this criteria for n = 5,6 and 7. If we further demand that at least 5 bins have excess in one region and deficiency in the other, 34 per cent of the miniruns have excess in A and deficiency in B, whereas 28 per cent have excess in B and deficiency in A. Therefore, it is possible that in VHE γ-ray studies, region B is populated by background events due to cosmic rays only, whereas the rest of the phase plot has events due to γ-rays also. A comment is in order about the non inclusion of the high χ^2_{19} group ($\chi^2_{19} > 1.8$). As mentioned above, the resultant χ^2_{19} of the phasogram in this group is not high. Further, the rank parameter is 106, giving a high probability that the two regions come from the same population. Therefore, it appears that the constituent miniruns of this group owe their high χ^2_{19} essentially to statistical fluctuations. We also note that if we remove the events from the main pulse and the interpulse regions from each minirun and then compute the χ^2_{17}, the summed phasogram of the miniruns in the $1{\cdot}4 < \chi^2_{17} \leqslant 1.8$ interval is flat.

For exploring further the differences between regions A and B, events in each minirun with $1.4 < \chi^2_{19} \leqslant 1.8$ were placed either in region A or in region B depending on their phase. For the two-bin phasogram thus obtained, χ^2_1 was computed. While three different (χ^2_1 > 1., 1.5, 2.) cuts were tried out, Fig. 2 displays the $\chi^2_1 > 2$ cut. The phasogram shows considerable excess at both the main and the interpulse phases. The average rate per minirun in regions A and B in Fig. 2 are 155.03 ± 0.80 and 147.90 ± 0.80 respectively. The average normal background rate (shown by the dashed line) was derived by ignoring the bins in the phase interval 0.95–0.10 and 0.40–0.45. This average rate for Fig. 2 is 149.9 ± 0.4 for half of the phase plot. Another measure of the normal background rate is obtained by comparing the rates before and after the 263 miniruns selected for Fig. 2. The pharograms of two miniruns just before and two miniruns just after the selected miniruns were pulled out and added up and the mean-rate obtained for either region was 148.9 ± 0.6. (Miniruns just before and after the selected minutes have better sensitivity to variations of atmospheric transparency and zenith angle.)

We consider here the reasons for high rate in region A. The value of δ, the excess number of events in region A was computed for each minirun. Miniruns with $+\delta$ and $-\delta$ were labelled as Type I and Type II respectively. R, the ratio of number of Type I to Type II miniruns, is 1.33 ± 0.16. At $\delta > 20$, R is 1.73 ± 0.27. Therefore, there are more Type I miniruns and that too with a higher rate in region A. Next, we compare the rate in each selected minirun with normal background average rate of 4 min which encompass it. The percentage of miniruns where region A (B) has fluctuated upward by $> 2\sigma$ is 17 (12) and downward by $> 2\sigma$ is 8 (18). The fluctuation of the normal cosmic ray background was computed and it was found that 20 per cent and 5 percent of the normal miniruns fluctuate beyond 1σ and 2σ for both A and B. (These differ slightly

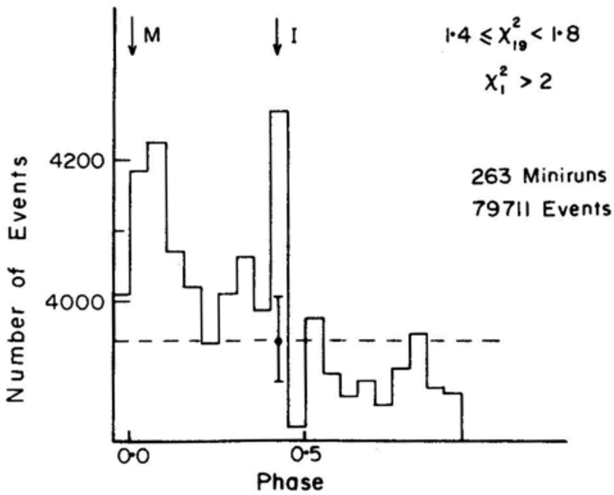

Figure 2. The summed phasogram of 263 miniruns which survive both the χ^2 cuts. The bimodal distribution is due to a dominant signal riding over the background due to cosmic rays.

from Poisson fluctuation because atmospheric transparency and extraneous lights play an important role in atmospheric Cerenkov methods.) The selected miniruns in which the total rate is lower than the normal cosmic ray background rate account for 42 per cent and 28 percent, of the excess seen in main pulse and interpulse respectively. Thus, the selection process has preferentially picked out miniruns where regions A and B have shown significant upward and downward fluctuation respectively.

We did a Monte Carlo simulation to see the probability of getting the distribution shown in Fig. 2. The observed average rate of 288 was chosen and each bin was given a Poisson fluctuated value, and thus a 20 bin phasogram was constructed. 10489 miniruns were generated as in the data and cuts identical to those made on the data were also applied to the simulated minutes. For each trial, a phasogram similar to Fig. 2 was obtained. We made a total of 1000 trials. While it was possible to get a distribution with one-half of the phasogram showing considerably large number of events compared to the other half (3 out of 1000 trials), this did not translate to significant peaks as seen in the data. Only one trial showed a single peak of statistical significance similar to those in Fig. 2. Therefore, to get at least two peaks of similar significance, the probability is 1×10^{-5} (Eadie *et al.* 1971). When we further demand that the two peaks be separated by 0.43 in phase, the probability is reduced to 1×10^{-6}. The higher-rate region was picked up for each trial and an average rate was obtained which was equal to 149.9 ± 0.4 per minirun. This rate, incidentally, is the same as that obtained by ignoring the peaks in the phasogram.

With this background rate, the Gaussian strengths of the main pulse and the interpulse in Fig. 2 are 5.9σ and 5.2σ. 142 out of 6146 miniruns at higher energy threshold (data sets I and III) and 123 out of 4343 miniruns at lower energy threshold (data sets II and IV) contribute to the phasogram in Fig. 2. The main pulse at low-and high-energy thresholds is at significance levels of 5.7σ and 1.9σ respectively. The interpulse at the low- and high-energy thresholds is at significance levels of 4.5σ and 3.0σ respectively. Fig. 3(a) shows the VHE γ-ray light curve from the present analysis for the lower threshold energy. The ordinate represents the number of events over and

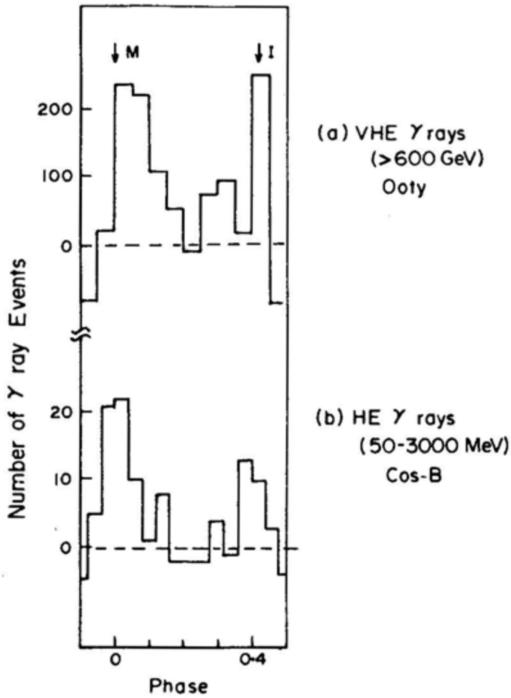

Figure 3. (a) The summed phasogram of miniruns at low-energy threshold (>600 GeV) which satisfy the criteria. The number in each bin is calculated after subtracting the background as mentioned in the text, (b) The light curve of high-energy γ-rays obtained by the Cos-B group in September 1980.

above the background, determined as explained in the earlier paragraph. Fig. 3(b) represents the rebinned light curve from the 1980 observations of the Cos-B group (Wills *et al.* 1972). The shapes of the two light curves are quite similar. While Dowthwaite *et al.* have a weak evidence for the interpulse, the present analysis is the only one to have shown the interpulse clearly at VHE γ-ray energies. The main pulse is wider (< 3.3 ms) than in the low-energy studies. In the VHE range there is no consensus about the width of the signal. Regarding time-averaged emission, Dowthwaite *et al.* saw a pulse with width less than 1 ms, whereas Tumer *et al.* reported the width to be 6 ms. In the burst measurements, Bhat *et al.* reported a width of 1.65 ms, whereas Gibson *et al.* had a much larger width. As for the possible smearing of the pulse due to inaccurate timekeeping, we would like to note that the Ooty time calibrations were done with a radio signal before 1984 and with a NNSS satellite time receiver after 1984 with timekeeping accuracies of ± 0.5 ms and 0.03 ms respectively. Further, the interpulse which is narrower appears in the same bin in all the 4 data sets. Therefore, it is quite possible that varied phenomena with slightly different widths are present.

The flux of VHE γ-rays from the Crab pulsar was obtained for energy thresholds of 600 Gev and 2200 Gev using the results of minirun analysis. The flux due to the main pulse alone is $(1.6 \pm 0.3) \times 10^{-10}$ $cm^2 s^{-1}$ and $(2.1 \pm 1.1) \times 10^{-11} cm^2 s^{-1}$ at E > 600 GeV and > 2200 GeV respectively. The main pulse flux at both energies agrees well with the expectations from Cos-B observations (at least 70 per cent of the Cos-B flux is due to the main pulse). In the observations on bursts (Bhat *et al.* 1986 and Gibson *et al.*

1983) and in the present work, the flux of the main pulse is $\geqslant 10^{-10} \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. We note that the time-averaged flux from the Crab pulsar is generally less than what is expected from observations at low energies. The agreement of a transient flux at TeV energies with what is expected from a time-averaged flux at low energies suggests (Porter 1983) that the Crab pulsar is capable of emitting considerable flux of VHE γ-rays.

4. Emission in individual runs

There were 65 runs in the whole data representing 65 independent nights of observation. When we consider the phasogram of individual runs, we find that the frequency with which the bin corresponding to either the main pulse or the interpulse is dominant ($>n\ \sigma$, with n= 1,2,3) is not much different from that for the other bins. Therefore, on the basis of this statistics, it is difficult to consider any particular run as being rich in γ-rays. However, special mention must be made of 4 complete runs from the 1984–1985 observations, where the phase region A had excess events on the same two nights at both the places. The summed phasograms for each site on these two nights (1985 January 23 and 1985 February 14) are shown in Figs 4(a, b). The total observation times at sites C and G were 150 min and 210 min respectively with overlap of 105

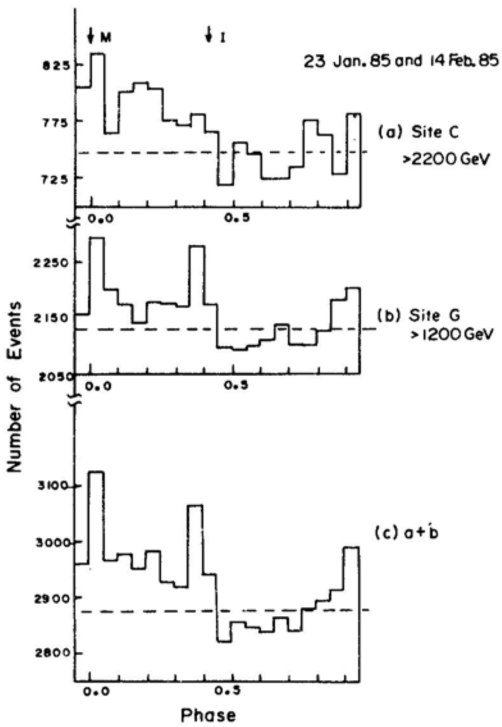

Figure 4. (a) The summed phasogram of all the data taken on two nights (see text) at site C where the energy threshold was 2200 GeV. (b) The summed phasogram of all the data taken on the same two nights at site G where the energy threshold was 1200 GeV. (c) The summed phasogram of data taken at sites C and G.

minutes. These two phasograms are further summed and the total phasogram for these two nights is shown in Fig. 4(c). The Wilcoxon's rank parameter is 56 for region A in Fig.4(c). If we consider the cosmic ray background to be given by the mean of region B then the main pulse is at 3.1 σ and 3.6 σ for the phasograms in Figs 4(a, b). The probability of occurrence of peak at the main pulse due to chance at both the sites is 4×10^{-6}. However, there were 7 nights of simultaneous observations and there are 21 ways of selecting two nights from the total of 7 nights. Therefore, the final probability of observing the main pulse in the season (1984–1985) when we had simultaneous observations is 8×10^{-4}. We should also note that the 15 min burst seen by Bhat *et al.* occurred on 1985 January 23.

5. Discussion

As for the time-averaged emission, the combined data of 4 data sets with absolute phase do not show any dominant peak. However, the upper limit in the present analysis does not disagree with the flux seen by Dowthwaite *et al.* at these energies. At the higher threshold energies (Data sets I, III and IV), there is a hint of a signal at the main pulse. There could be two reasons for the lowest threshold data not showing any signal: (a) The steady emission has seasonal variations and the Crab pulsar did not have, any emission during that season. (b) The lowest threshold also meant a higher trigger rate (because of use of all mirrors and a larger aperture) and it is possible that more noise (cosmic rays) was admitted into the system. We should, however, note that while the University of Durham group did find a signal in 1982–1983, 34 hours of observation in 1981 did not show any such signal.

We would like to note that one-minute activities reported here do not refer to the strong emission from the pulsar. The nomenclature 'burst' traditionally refers to the activity of the pulsar over and above the normal background (*cf.* Bhat *et al.* 1986; Gibson *et al.* 1982). The present analysis does not require a high signal level. In fact, out of the 263 miniruns selected for the final plots, the ratio of the number of miniruns with any bin in region A having > n σ peak (with n =1,2,3) to the number with any bin in region B showing a similar peak, decreases from 1.26 ±0.7 at n = 1 to 1.1 ±0.2 at n= 3. Thus, most of the events in the signal come from miniruns where the peak is present but not at any high intensity. Therefore, it is the low-level transient emission which gets picked up by this method. It is interesting that while most of the earlier efforts look for a transient signal in a region with higher emission rate (*e.g.,* Gibson *et al.*)*,* the method outlined here searches for minutes with low rates also. However, one should note that this analysis is not expected to pick out constant and weak signals. The flux seen by Dowthwaite *et al.* (1984) results in about one γ-ray event in 17 minutes and will not be detected irrespective of how low the background may fluctuate.

As for the emission over timescales of a few hours, the data on individual runs show that such emission is in general not present. However, our 1984–1985 observations were done at two well separated sites (Bhat *et al.*) and two out of seven nights of observation did show the main pulse at a level > 3 σ. It is interesting to compare Fig. 4(c) and Fig. 2 since both display a main pulse and a rather bimodal distribution. Fig.2 is a result of the minirun analysis and all the data sets contribute to it. Fig.4(c) represents the complete data of two nights. While Fig. 2 is a possible result of both the presence of a signal in region A and a statistical downward fluctuation of the cosmic ray background, it is highly unlikely that the background has fluctuated downward on both the nights and at both the sites. Therefore, Fig. 4(c) can be accounted for only by increased γ-ray activity on those two nights. Another interesting aspect of these two phasograms is that there seems to be some emission from the middle phase regions also. The number of events in the middle phase region is much higher than the background. In effect, regions A and B can be considered to be the 'on' and the 'off' regions for the pulsar. However, the emission is from the pulsar and not from the nebula since periodicity has been invoked.

6. Conclusions

In summary, a new analysis of the Ooty data has shown that it is more likely that the Crab pulsar emits VHE γ-rays on a shorter timescale rather than on a larger timescale. While the emission over a timescale of years is barely detectable, the analysis has evidence for emission over timescales of minutes and possibly hours. The analysis shows the main pulse and the inter pulse from the Crab pulsar with a low probability that they are due to chance. These pulses have been seen at both low- and high-energy thresholds and in all four data sets. The analysis has located minutes where the pulsar is active. It is easier to discern low-level activity when the background undergoes a downward fluctuation. As for emission over a few hours, our most recent observations on Crab pulsar also showed the main pulse on two nights of simultaneous observations. In the emission over both minutes and hours, there are γ-rays from in between the main and interpulse region. The observed flux in the miniruns, which is similar to transient fluxes determined in observations on bursts, shows that the pulsar iscapable of emitting considerable amount of γ-rays.

Acknowledgements

It is a pleasure to thank Professors P.V. Ramanamurthy, M. V. S. Rao, B. V. Sreekantan and Dr B. K. Chaterjee for useful discussions on the manuscript. Professors P. V. Ramanamurthy and S. C. Tonwar, and Drs P. N. Bhat and S. K. Gupta are thanked for their contributions to the observation and analysis. Mr A. R. Apte is thanked for designing and setting up the array and also for assistance during the observations. Messrs N. V. Gopalakrishnan, R. Mahalingam, R. Ramani, S. Swaminathan and M. Venkateshwarlu are thanked for the design and testing of electronics and assistance during the observations. Drs P. T. Wallace and A. J. Lyne graciously provided the pulsar elements.

References

Bhat, P. N., Ramanamurthy, P. V., Sreekantan, B. V., Vishwanath, P. R. 1986, *Nature,* **319,** 127.

Dowthwaite, J.C, Harrison, A. B., Kirkman, I.W., Macrae, H. J., McComb, T. J. L., Orford, K.J., Turver, K. E., Walmsley, M. 1984, *Astrophys. J.,* **286,** L35.

Eadie, W. T., Drijard, D., James, F. E., Roos, M., Sadaoulet, B. 1971, *Statistical Methods in Experimental Physics,* North Holland, Amsterdam.

Frodesen, A. G., Skeggestad, O., Tofte, H. 1979, *Probability and Statistics in Particle Physics,* Universitetsforlaget, Bergen, 453.

Gibson, A. I., Harrison, A. B., Kirkman, I. W., Lotts, A. P., Macrae, J. H., Orford, K. J., Turver, K. E., Walmsley, M. 1982, *Nature,* **296,** 833.

Gupta, S. K., Ramanamurthy, P. V., Tonwar, S. C, Vishwanath, P. R. 1985, *Astrophys. Space Sci.,* **115,** 163.

Porter, N. A. 1983, in *Proc. of XVIII Int. Conf. on Cosmic Rays,* **12,** 435.

Tumer, O. T., Wheaton, W. A., Godfrey, C. P., Lamb, R. C. 1985, in *Proc. IX Int. Conf. on Cosmic Rays,* **1,** 139.

Vishwanath, P.R.1982, in *Proc. Int. Workshop on Very High Energy Gamma Ray Astronomy,* Eds. P. V. Ramanamurthy & T. C. Weekes, TIFR, Bombay, p. 21.

Wills, R. D., Bennet, K., Bignami, G. F., Buccheri, R., Caraveo, P. A., Hermsen, W., Kanbach, G., Masnou, J. L., Mayer-Haselwander, H. A., Paul, J. A., Sacco, B. 1982, *Nature,* **296**,723.