Astron. Astrophys. 245, 141–144 (1991)

ASTRONOMY
AND
ASTROPHYSICS

Evidence for pulsed emission from the Crab pulsar at PeV energies: Ooty observations during 1984–87

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Received October 11, accepted November 9, 1990

Abstract. Ooty database consisting of nearly 7 million air showers of energies $>2\,10^{14}$ eV collected during 1984–87 has been analysed for detection of ultra high energy radiation from the Crab pulsar and nebula. No significant time-averaged excess has been observed from the direction of the Crab pulsar/nebula. However, a search of these data for pulsed flux has yielded significant evidence for emission which is time-coincident in phase with the optical interpulse in the light curve of the Crab pulsar, PSR 0531 + 21. The pulsed flux is nearly constant with time over the three years of observations. Data also show that the average age of the showers ascribed to pulsed flux from the Crab pulsar is larger. These observations correspond to a time-averaged pulsed flux of $(4.1 \pm 1.2)\,10^{-13}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ from the Crab pulsar at energies $>2\,10^{14}$ eV.

Key words: cosmic rays – extensive air showers – gamma-rays – pulsars

1. Introduction

The Crab nebula is a unique astrophysical laboratory with energetic processes dominating its evolution. It has been the most studied source at all wavelengths, from radio to the highest energies. Early observations of a high level of polarization at radio, optical and X-ray wavelengths confirmed the presence of relativistic electrons in the nebula. These observations led to the suggestion that the nebula was a strong cosmic ray source accelerating protons to high energies and producing high energy gamma rays through production and decay of pions. It was one of the first sources studied for detection of gamma-rays at TeV energies in early 1960's although with negative results. The discovery of a young and fast (936 yr, 33 ms) pulsar in 1968 (Staelin & Reifenstein 1968) generated further interest in this source. Soon there were theoretical predictions suggesting acceleration of particles, electrons, protons and ions, by the rotating magnetized neutron star to energies of 10^{14} eV and higher.

Pulsed flux of gamma-rays from the Crab pulsar (PSR 0531 + 21) has been observed by balloon and satellite (SAS-II and COS-B) borne detectors upto energies of few GeV (McBreen et al. 1973; Greisen et al. 1975; Thompson et al. 1977; Wills et al. 1982). There are also several reports of detection of sporadic flux of gamma-rays at TeV energies, in both, steady and pulsed modes (see the review by Weekes 1988). Very recently, the Whipple collaboration (Weekes et al. 1989) has been successful in overcoming the problems due to cosmic ray background by exploiting the differences in images made by Cherenkov photons in the focal plane of a large 10 m diameter reflector at Mount Hopkins, Arizona. They have reported detection of a steady and mostly unpulsed flux of TeV photons from the Crab pulsar/nebula at a very high significance level. Interestingly the shape of the light curve for the Crab pulsar, showing a double pulse structure with 13.6 ms separation between the main pulse and the interpulse, has been identical for photons of all energies, from 10^{-6} eV to 10^{9} eV. This is in sharp contrast to the Vela pulsar whose light curve shows completely different features at radio, optical and gamma-ray energies. Observations (Wills et al. 1982) at gamma-ray energies (>30 MeV) have also shown significant change in the relative amplitudes of main and interpulse with time.

Several attempts have been made to detect flux of ultra high energy (UHE) photons from the Crab pulsar/nebula using extensive air shower (EAS) arrays or atmospheric Cherenkov radiation techniques. Using shower data obtained with Lodz array during 1968–71 and 1975–79, Dzikowski et al. (1981) have claimed detection of gamma-ray flux of $2\,10^{-13}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at energies $>10^{16}$ eV from the Crab pulsar/nebula. However, a very poor angular resolution of the array forced the authors to bin showers in large size angular bins (37°5 in right ascension), the identification of the observed excess to be due to Crab nebula may be considered as somewhat speculative. The observed excess was mainly among muon-poor showers, a signature expected if the primaries are photons. These observations, however, do not find support from data taken with Haverah Park array. With improved angular resolution (6° × 6° bins), Watson et al. (1985) have put an upper limit on the flux of radiation from the Crab pulsar/nebula at $1.5\,10^{-15}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at energies $>10^{16}$ eV. At somewhat lower energies, Kirov et al. (1985) have reported detection of gamma-rays from the Crab pulsar/nebula from their observations at Tien-Shan during 1974–82 with flux of $(2.8 \pm 0.8)\,10^{-13}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at energies $>3.5\,10^{14}$ eV. Poor angular resolution for the array has forced these authors also to bin showers in large size angular bins (15° in RA) but they also find the signal only among muon-poor showers. Since all these observations were spread over several years and did not have good enough timekeeping for pulsation analysis of data, they have not provided any information on the pulsed content of the flux at PeV energies (1 PeV = 10^{15} eV).

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Detection of a burst of showers from the direction of the Crab pulsar/nebula at PeV energies was first reported by Boone et al. (1984) but the statistical significance of the positive effect was rather small. Recently Alexeenko et al. (1989) and Acharya et al. (1990) have reported observing an increase in the number of showers observed from the direction of the Crab pulsar/nebula on February 23, 1989. Detection of a burst of UHE photons from the Crab pulsar/nebula lasting for more than 8 h has been claimed from these observations.

We report here the results of analysis of data collected with the EAS array at Ooty during 1984–87 for detection of pulsed flux from the Crab pulsar at energies $>2\ 10^{14}$ eV. Our analysis reveals a statistically significant pulsed signal which is time-coincident in phase with the optical interpulse in the light curve of the Crab pulsar, PSR 0531 + 21. Some relevant details about observations at Ooty and data analysis are summarised in Sect. 2. Results obtained from these observations are presented in Sect. 3. A comparison of flux detected at Ooty with other observations and the energy spectrum inferred from these observations for the pulsed flux from the Crab pulsar at PeV energies are discussed in Sect. 4. The conclusions drawn from this study are given in the last section.

2. Observations and data analysis

Data have been collected with the 24 scintillation detector array operating at the mountain altitude (2200 m) laboratory at Ooty (11°.4 N latitude) in southern India during June '84–May '87 (1043 days). All showers recorded during this period have been analyzed for arrival direction, core position, lateral distribution parameters (age) and shower size. The age of a shower (Greisen 1956) is a measure of its development at the observational depth in the atmosphere (800 g cm^{-2} at Ooty). A total of $6.9\ 10^6$ showers constitute the final database for studies on emission of PeV energy radiation from various interesting astrophysical sources. Details of the experimental system, trigger logic, data acquisition and analysis procedures have been discussed elsewhere (Tonwar 1985; Tonwar et al. 1985; Tonwar et al. 1988 ; Gupta et al. 1990). The effective shower size threshold for the Ooty array is $5\ 10^4$ corresponding to an energy threshold of $2\ 10^{14}$ eV. The angular resolution of the array has been estimated (Tonwar 1985; Gupta and Tonwar 1991) to be 1°.6. Therefore a 4° × 4° bin in right ascension (RA) and declination (DEC), centred on the Crab pulsar ($\mathrm{RA}_{86} = 83^\circ.3$, $\mathrm{DEC}_{86} = 22^\circ$) has been designated as the source bin for all studies on this source. The other 89 bins of same size and at same declination but shifted successively by 4° in RA are used for estimating the background during the search for steady flux from the pulsar.

3. Results

3.1. *Search for steady flux from Crab pulsar/nebula*

The number of showers observed in the source bin centred on the pulsar over the entire observational period is 3536. These showers satisfy the following "good quality data" criteria: (a) shower size $N_e > 5\ 10^4$, (b) core distance from the centre of the array $R_c < 30$ m, and (c) zenith angle $< 40°$. The expected number of showers for the background as obtained from the average of 89 off-source bins is 3460. The excess of 76 showers in the source bin, a fluctuation of 1.3σ above the expected background, is not significant statistically. Some of the earlier observations, particularly on Cygnus X-3 (Samorski & Stamm 1983; Tonwar et al. 1988), have suggested that selection of older showers enriches the sample with photon-initiated showers. However, for showers arriving from the direction of the Crab pulsar, a selection on age (> 1.1, the median value) does not lead to a significant enhancement of the excess relative to the background. Other selection criteria, such as a higher energy threshold, also have not shown any significant effect on the signal to background ratio. These observations therefore have been used to place a 99% confidence level (CL) upper limit of $7.7\ 10^{-13}$ cm^{-2} s^{-1} on the time-averaged flux from the Crab pulsar/nebula at energies larger than $2\ 10^{14}$ eV.

3.2. *Search for episodic flux from Crab pulsar/nebula*

Evidence was recently presented (Gupta et al. 1990; Tonwar et al. 1990) for episodic emission from Her X-1 and Cyg X-3 using a search program that looks for days with significant excess of events in the source bin. We have searched for episodic emission from the Crab pulsar/nebula using a similar approach. For this purpose, data collected only during "good" days were considered for further analysis to avoid any systematics. A "good" day was defined as a day when the observation on PSR 0531 + 21 lasted for 320 min as the source moved sidearally from 40° east to 40° west. A total of 675 days satisfied this criterion. The average shower rate in the source bin is 4.31 per "good" day. The distribution of number of showers per "good" day, extending from 0 to 12, is fully consistent with expectations from Poisson distribution. We therefore conclude that there is no evidence in Ooty data for any sporadic activity at ultra high energies from the direction of the Crab pulsar/nebula during 1984–87, similar to the burst detected by Baksan (Alexeenko et al. 1989) and KGF (Acharya et al. 1990) groups in February 1989.

3.3. *Search for pulsed flux from Crab pulsar*

Data for the source bin centred on the Crab pulsar/nebula have also been searched for pulsed flux. The time of occurrence of each shower is recorded to a precision of 0.1 ms and is known to an accuracy of 0.5 ms in absolute time (UT). Observed times of all showers in the source bin have been reduced to the arrival times at the solar system barycentre using the MIT PEP-311 program. The phase for each shower is then computed using the Crab pulsar ephemeris given by Lyne et al. (1988, 1989) which is based on long term observations of the pulsar at Jodrell Bank. The phas[illegible] histogram obtained for all showers in the source bin is shown in Fig. 1a. The expected positions of the centres of the main pulse and interpulse are shown in the figure by arrows. The light curves for the Crab pulsar at energies of 50–500 MeV observed during early 1970's (Thompson et al. 1977) and late 1970's (Wills et al. 1982) from observations with detectors aboard the SAS-II and COS-B spacecrafts are shown in Figs. 1b and 1c respectively for comparison. It is evident that the peak seen in Fig. 1a is coincident with the expected position of the interpulse while there is no significant excess coincident with the main pulse.

Summing over the two bins which show excess counts in Fig. 1a, there are a total of 420 showers in these two bins compared to the expected background of 347 showers, which is the average obtained from data of the other 18 bins. A conservative estimate of the probability for observing this excess of 73 showers (3.9σ) coincident with the phase of either the main or the interpulse or anywhere in the phase histogram by chance is rather small, $20 \times 8.0\ 10^{-5}$, that is $1.6\ 10^{-3}$. The factor 20 is included here to allow for the fact that there are twenty bins in the phase histogram and the observed excess need not have been coincident with the main pulse or the interpulse to be considered significant. This excess of 73 showers corresponds to a pulsed flux of $(4.1 \pm 1.2)\ 10^{-13}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ from the Crab pulsar at energies $> 2\ 10^{14}$ eV.

We have studied the variation of the excess at the phase of the interpulse as a function of time by dividing the three year database into 6 intervals, each of duration of approximately 6 months. The number of showers in the two bins corresponding to the interpulse and the expected number as obtained from the average of other 18 bins for the 6 intervals are as follows: 62/45.1, 62/53.4, 77/64.7, 77/56.0, 55/61.5, and 87/66.3. It is interesting that except for the 5th interval (May–November 1986) which has shown a deficit in the number of showers in the interpulse region compared to the expected background, all the other five data sets show an excess. Statistically, these data do not reveal any evidence of large scale variation in pulsed flux with time over the three years of observations at Ooty.

Since the pulsation period for the Crab pulsar is much shorter (33 ms) than the average time interval between showers (4000 s) recorded in the experiment, there is no possibility of any systematic effect in the phase histogram due to uneven exposure for different bins. Therefore we have used all the showers in the source bin for obtaining the light curve shown in Fig. 1a independent of the length of the run on each day. However, we have also studied the possibility of the observed signal arising mainly due to many small bursts. For this purpose, we have looked at phase distributions for showers observed on days when the number of showers in the source bin was larger than the average. There is no evidence for any statistically significant correlation of the signal strength with observed shower rate in the source bin.

We have also studied the dependence of the observed signal amplitude on age of showers since earlier observations on Cyg X-3 (Samorski & Stamm 1983; Tonwar et al. 1988) have shown a significant enhancement of the signal among older showers. The phase distribution for older showers (age > 1.4) only is shown in Fig. 1d. It is rather interesting that there is an excess of 35 (3.7σ) showers in the interpulse region above the expected background of 92.1. The probability for this to occur by chance is $2.2\ 10^{-4}$. However, these showers do not constitute an independent data set as they are a sub-set of showers used for the plot shown in Fig. 1a. It is of interest to note that the signal strength relative to cosmic ray background is almost double among older showers, 35/886 i.e. 4.0%, compared to all showers, 73/3470 i.e. 2.1%. A proportional reduction of signal, if there was no age correlation, would have reduced the excess among older showers to only 19 (2.0σ). The probability for this enhancement in signal strength to be due to statistical fluctuations has been estimated by Monte Carlo simulations to be only 1.5%. These results may be considered as providing support to the observational hypothesis (Samorski & Stamm 1983; Tonwar et al. 1988) that a cut on shower age (> 1.4) preferentially selects photon-initiated showers. However, according to simulations (Cheung & Mackeown 1987 and references therein), the expected age distribution for photon-initiated showers is not significantly different from those initiated by protons.

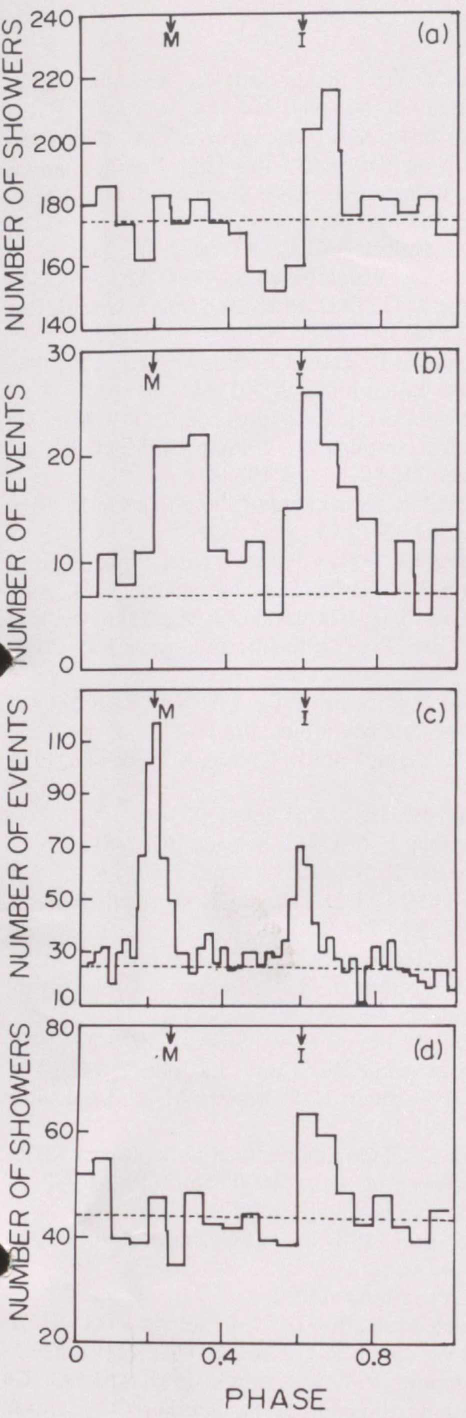

Fig. 1 a–d. Phase distributions for events in the source bin centred on the Crab pulsar: **a** all showers observed at Ooty during June 1984–May 1987, **b** gamma-rays observed by detectors aboard SAS-II, **c** gamma-rays observed by detectors aboard COS-B, and **d** only showers with age > 1.4

4. Discussion

The value of the pulsed flux determined from the observed excess (Fig. 1a) may be compared with other measurements. However it should be noted that since this is the first ever observation of pulsed flux from the Crab pulsar at PeV energies, no direct comparison is possible with other experiments. The pulsed flux value, $(4.1 \pm 1.2)\ 10^{-13}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for energies $> 2\ 10^{14}$ eV, obtained from Ooty observations is comparable with the time-averaged flux value of $(2.8 \pm 0.8)\ 10^{-13}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at energies $> 3.5\ 10^{14}$ eV given by Kirov et al. (1985). However, the observed flux at Ooty is much smaller than the flux expected from the measurements at energies $> 10^{16}$ eV reported by Dzikowski et al. (1981). The gamma-ray luminosity of the Crab pulsar/nebula at energies $> 2\ 10^{14}$ eV is estimated to be $1.5\ 10^{35}\,\mathrm{erg\,s}^{-1}$, assumming isotropic emission and a differential power law energy spectrum with exponent of -2.7. This is a small fraction of the rotational energy loss ($4.7\ 10^{38}\,\mathrm{erg\,s}^{-1}$, Taylor & Manchester 1975) for the pulsar. It is therefore considered necessary that further systematic observations be carried out on the pulsed component of the flux at PeV energies from the Crab pulsar with larger shower arrays, particularly with those which have large area muon detectors. New observations would help in confirming the Crab pulsar to be a source of pulsed flux at PeV energies. Such observations are also needed to establish the photonic nature of this radiation and for learning about the nature of photon interactions at these ultra high energies. However, results presented here do suggest that radiation detected at PeV energies is photonic in nature by virtue of the fact that the pulsed flux is aligned in phase with the interpulse at lower energies, from 10^{-6} eV (radio) to 10^{14} eV.

5. Conclusions

Data collected with the EAS array at Ooty during 1984–87 have been analysed to search for steady and pulsed flux of radiation from the Crab pulsar/nebula at energies $> 2\ 10^{14}$ eV. No time-averaged steady flux has been detected from the Crab pulsar/nebula and a 99% CL upper limit of $7.7\ 10^{-13}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ has been placed on the emission of steady flux from the nebula at energies $> 2\ 10^{14}$ eV. A pulsed flux of $(4.1 \pm 1.2)\ 10^{-13}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ has been detected from the Crab pulsar for the first time at these ultra-high energies. Significantly, this flux is time coincident with the optical interpulse in the light curve for the pulsar.

Acknowledgements. We thank A.R. Apte, G. Asok Kumar, S.G. Bhargavi, N.V. Gopalakrishnan, T.S. Selvakumaran, and S. Suresh for providing excellent scientific support during data-taking. We are grateful to Dr. Andrew Lyne for providing the ephemeris for the Crab pulsar.

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Detection of Ultrahigh-Energy Radiation from Scorpius X-1: Ooty Observations during 1984–1987

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(Received 8 April 1991)

A detailed study of showers arriving from the direction of Scorpius X-1 has shown strong evidence for emission of ultrahigh-energy radiation from Scorpius X-1 during the period 4 March–2 May 1986. 178 showers were observed in the source bin against an expected background of 122.9. The chance probability for observing this excess has been estimated from simulations to be less than 10^{-3}. The flux observed during this period was $(6.4 \pm 1.6) \times 10^{-12}$ cm^{-2}s^{-1} at energies $> 2.5 \times 10^{14}$ eV, corresponding to a luminosity of 2×10^{35} ergs s^{-1}.

PACS numbers: 98.70.Rz, 95.85.Qx, 97.80.Jp, 98.70.Sa

Several x-ray binaries, for example, Cygnus X-3, Hercules X-1, Vela X-1, and Centaurus X-3, have been observed to be sources of ultrahigh-energy (UHE, $> 10^{14}$ eV) radiation during the 1980s (see Fegan [1] for a recent review). Some of these observations have also shown evidence (Tonwar [2], and references therein) for significant time variability in the flux. In this Letter we present evidence for emission of UHE radiation from Scorpius X-1 and its temporal variation.

Scorpius X-1 is a nearby (~500 pc) x-ray binary which shows quasiperiodic oscillations in x-ray flux [3]. These observations have been interpreted to suggest the presence of a neutron star with a rotation period of a few milliseconds which powers the high-energy emission from this source. A 95% C.L. upper limit of 1.6×10^{-10} cm^{-2} s^{-1} was placed on the time-averaged steady flux from Scorpius X-1 by Protheroe and Clay [4] at energies $> 4 \times 10^{15}$ eV from observations during 1979–1981. However, Scorpius X-1 has been suggested to be a variable source of UHE radiation by Matano *et al.* [5] from observations at Chacaltaya. Recently, Brazier *et al.* [6] have detected Scorpius X-1 at energies > 300 GeV.

Among many air-shower arrays operating in the northern hemisphere, the array at Ooty (11.4° N latitude, 2200 m altitude) in southern India has the capability to observe some of the southern sources, such as Scorpius X-1. Data have been collected with the 24-scintillation-detector array at Ooty from June 1984 to May 1987. Showers were selected with a fourfold coincidence between detectors located near the center 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. All showers recorded during this period have been analyzed [7–10] for arrival direction (zenith angle θ, azimuth ϕ, right ascension α, and declination 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 database for studies on cosmic sources. The effective shower-size threshold for the array was 5×10^4, corresponding to an energy threshold of 2.5×10^{14} eV for showers arriving at $\theta = 27°$, the angle for Scorpius X-1 at meridian transit. The angular resolution of the array has been estimated [11] to be 1.6°. Consequently a 4°×4° bin in α and δ, centered on Scorpius X-1 ($\alpha = 244.8°$, $\delta = -15.6°$) has been designated as the source bin.

Using the entire database, we have looked for directional excess in the source bin relative to the mean of 89 other α bins at the same declination ($-15.6° \pm 2.0°$). Cuts on core distance ($r_c < 30$ m) and zenith angle ($\theta < 40°$) imposed on data ensure better accuracy for various shower parameters. A total of 1700 showers were observed in the source bin compared to the mean of 1693.2 ± 4.4 for the 89 other α bins. A 99% C.L. upper limit of 5.3×10^{-13} cm^{-2} s^{-1} has been obtained for the steady flux from Scorpius X-1 at energies $> 2.5 \times 10^{14}$ eV from Ooty data.

Matano *et al.* [5] have observed an excess in the number of hadronless showers arriving from within 7° of Scorpius X-1 during May 1986 and the excess flux has shown modulation with the 18.9 h binary period. A similar enhancement in UHE flux over a time scale of a few weeks has been observed [2] for Cygnus X-3. We have examined Ooty data for evidence of possible enhancement in flux from Scorpius X-1 over a time scale of a few weeks.

Since there is a significant variation in the observed shower rate as a function of the zenith angle of the source bin, we have restricted our analysis here to data of only "good" days. Eight α bins at the same declination as Scorpius X-1, four on either side but excluding the α bins adjacent to the source bin, provide an estimate of the background. 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 min as the source moved from 30° E to 30° W ($\theta < 40°$). During the nearly 3 yr of observations, there were a total of 726 good days for the source bin with a mean shower rate of 2.121 ± 0.054 d^{-1}. The mean shower rate for the background bins was 2.026 ± 0.019 d^{-1}. The observed excess in the shower rate, 0.095 ± 0.057 d^{-1}, is not significant statistically.

Since this low value 2.121 ± 0.054 d^{-1} of the shower rate does not permit a meaningful study of the day-to-day rate variation, the weekly shower rate has been studied. Note that a period of one week does not necessarily consist of seven consecutive calendar days, since runs were occasionally interrupted on some days due to breakdown in either electrical power or instrumentation. The difference in the weekly shower rate between the source and the mean of the eight background bins is shown in Fig. 1(a) for the entire observation period of 102 weeks. No unusually large excess is seen in this figure for any individual week. However, a positive excess is clearly noticeable for several consecutive weeks over the period March–May 1986, which is marked by arrows in the figure. Note that Matano *et al.* [5] have reported the observation of a significant excess in the number of hadronless showers from the direction of Scorpius X-1 during May 1986. A replot of the data shown in Fig. 1(a), summed over consecutive two-week intervals, is shown in Fig. 1(b). The excess during the marked period is now conspicuous in this figure. The variation in the excess with time, further summed over a consecutive pair of bins, is shown in Fig. 1(c), which clearly defines the outline of the observed excess. It is seen to be confined to the eight-week time interval starting from 4 March 1986. Finally, data summed over consecutive eight-week time intervals and plotted in Fig. 1(d) show a very significant excess in the number of showers observed from the direction of Scorpius X-1 relative to the background region during the period 4 March–2 May 1986. It is evident from the discussion above that no attempt has been made to optimize the observed excess by selecting the first or the last day of the time interval. A total of 178 showers were observed in the source bin during the period 4 March–2 May 1986 against an expected number of 122.9 ± 3.9. The Poisson probability for this excess (4.97σ) is 1.8×10^{-6}.

Monte Carlo simulations have been carried out to estimate the probability for observing 178 showers for any eight-week time interval out of a total of 102 weeks for the average background weekly rate of $122.9/8 = 15.4$ from Poisson fluctuations. In fact, simulations have been carried out to determine the probability of observing an equivalent 4.97σ $[(178-122.9)/\sqrt{122.9}]$ excess in any combination of data of contiguous weeks. Using the average weekly shower rate of 15.4, the number of showers expected in each of the 102 weeks are generated from the Poisson distribution and this set of simulated data for 102 weeks forms one "Ooty observation." Using this data set, 102 one-week, 101 two-week, 100 three-week, . . . , and one 102-week combinations are formed by adding successive weeks of data. All these (5253) combinations are then scanned to detect any occurrence of an equivalent excess $\geq 4.97\sigma$ relative to the average for the corresponding combination. A total of 991 out of 10^6 Ooty observations showed an excess $\geq 4.97\sigma$.

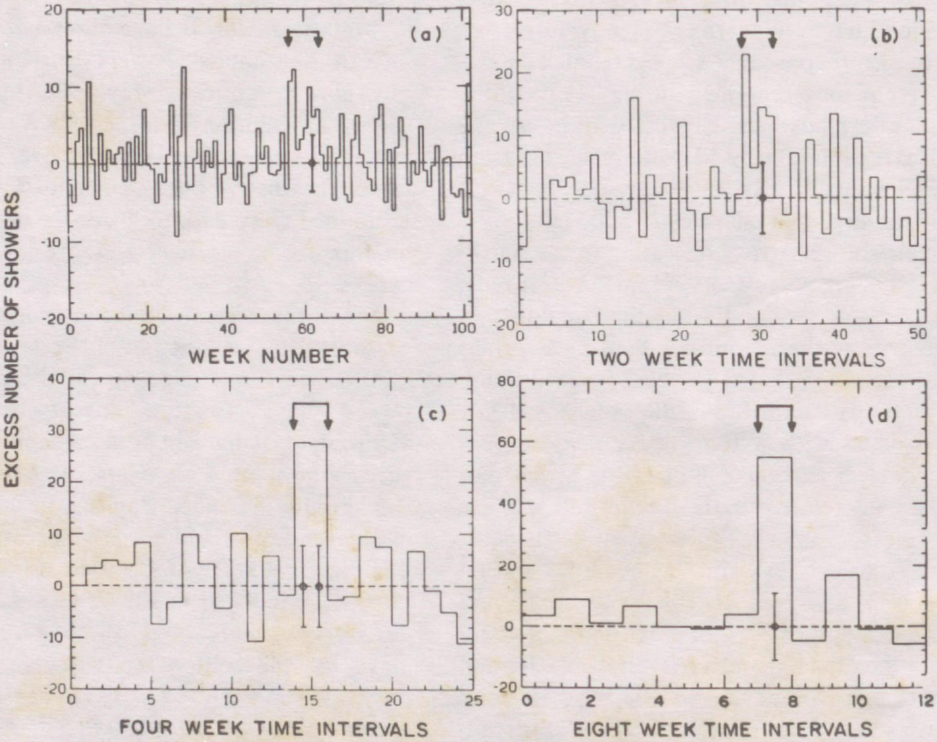

FIG. 1. Variation in the excess number of showers observed in the source bin relative to the average number observed in the background region as a function of time: (a) one week, (b) two weeks, (c) four weeks, and (d) eight weeks. The arrows indicate the period 4 March–2 May 1986.

Therefore, the upper limit on the chance probability for observing an excess $\geq 4.97\sigma$ in any combination of data for one or more successive weeks out of 102 weeks is estimated to be $991/10^6 = 9.9\times10^{-4}$.

These simulations have shown that the number of degrees of freedom are severely constrained when considering all the possible combinations within a single data set of 102 weeks. The effective number of degrees of freedom is only $9.9\times10^{-4}/1.8\times10^{-6} = 550$, though the total number of combinations is 5253. It should be emphasized here that the real data were not scanned for the excess in this manner and the probability of 9.9×10^{-4} obtained from simulations is an upper limit.

Ooty observations may therefore be considered to confirm Scorpius X-1 to be a source of UHE radiation. They also show that the UHE flux from Scorpius X-1 varies significantly over a time scale of a few weeks. The flux from Scorpius X-1 at energies $> 2.5\times10^{14}$ eV has been estimated to be $(6.4\pm1.6)\times10^{-12}$ cm^{-2}s^{-1} during this eight-week period. The measured value of the flux corresponds to a gamma-ray luminosity of 2×10^{35} ergs s^{-1} for Scorpius X-1 at energies $> 2.5\times10^{14}$ eV, assuming isotropic emission and an index of -2.6 for the differential power-law energy spectrum.

The signal from Scorpius X-1 has been observed at Ooty during the period 4 March–2 May 1986, while Matano *et al.* [5] have observed a significant excess from the direction of Scorpius X-1 only during May 1986. This apparent lack of time overlap between the two observations can be easily understood in terms of statistical fluctuations. The total number of excess showers observed by Matano *et al.* during May 1986 which could be ascribed to Scorpius X-1 was only 6. The binary phase for most of these 6 showers was near 0.2. In view of such a limited statistics for the Chacaltaya experiment, it is quite likely that a similar increase in the flux during March–April 1986 may have been missed statistically. In fact, this possibility becomes more likely given the sporadic nature of the source as revealed by the analysis of "doubles," discussed later. Also to be noted is the fact that Ooty and Chacaltaya cannot observe a source simultaneously due to a difference of nearly 10 h in longitude.

We have also looked for enhancement in flux from Scorpius X-1 over a time scale of several minutes, as has been observed for some other binary sources [2,12–14]. This has been done through a study of doubles. A double is, *a priori*, defined as a shower in an α bin followed by a second shower (in the same bin) within a time interval of 15 min. The time interval of 15 min was chosen because of several observations of bursts in VHE (10^{12} eV) and UHE flux over similar time scales. This time interval was also considered as suitable for the study of time clustering in Ooty data since the mean separation between showers in any α bin was > 60 min. The mean number of doubles observed in the Scorpius X-1 bin was 0.330 ± 0.021 d^{-1}, compared to 0.262 ± 0.007 d^{-1} for the eight background bins. Figure 2 shows the variation in the number of doubles observed per week for the source bin (solid line) and the background (dashed line). Figure 3 shows a replot of the same data for eight-week time intervals. It is interesting to note from these two figures that there is a very significant increase in the number of doubles during the same eight-week time interval, 4 March–2 May 1986, when there was a large enhancement in the shower rate (Fig. 1). Forty-eight doubles have been observed in the source bin during this period compared to the mean number of 16.75 ± 1.45 in the background region.

The probability for the occurrence of a double cannot be evaluated directly by using the mean shower rate, since the shower rate varies significantly over the 240 min

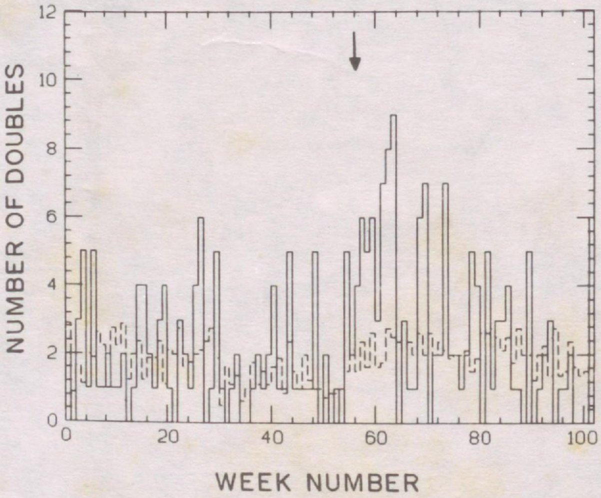

FIG. 2. Variation in the number of "doubles" observed per week from the direction of Scorpius X-1 (solid lines) and from the background region (dashed line), as a function of time. The arrow indicates the week starting on 4 March 1986.

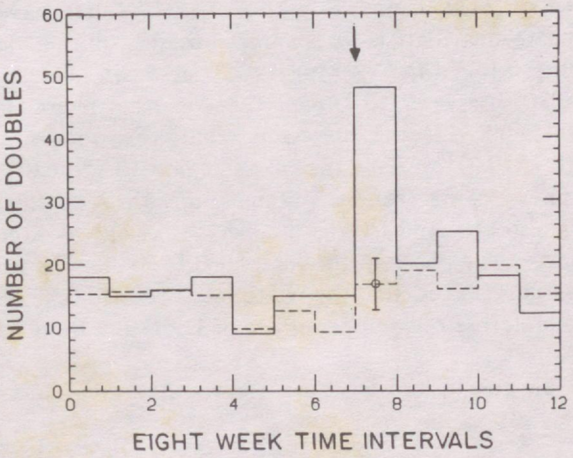

FIG. 3. Variation in the number of "doubles" observed during eight-week time intervals from the direction of Scorpius X-1 (solid line) and from the background region (dashed line), as a function of time. The arrow indicates the week starting on 4 March 1986.

of observation during a day due to its dependence on the zenith angle. Therefore, we have carried out Monte Carlo calculations to estimate the frequency of the occurrence of doubles using the observed shower rate and the observed variation of shower rate with zenith angle, simulating [2] exactly the zenith-angle sweep by the source region centered on the declination of Scorpius X-1. With a mean shower rate of $2.121 \pm 0.054\ \mathrm{d}^{-1}$ for the source bin, simulations predict the double rate to be $0.281\ \mathrm{d}^{-1}$, which is slightly smaller than the observed rate of $0.330 \pm 0.021\ \mathrm{d}^{-1}$. However, the agreement between the expected and the observed double rates becomes excellent if the eight-week time interval 4 March–2 May 1986 is excluded. Note that both the shower rate and the double rate have shown very significant enhancement during this period. The number of doubles expected during the remaining 94 weeks is 184.9—in excellent agreement with the observed number of 192. There is also good agreement [2] between simulations and observations for the distribution of the number of doubles per day, both for the source bin as well as the background region.

Using the mean shower rate of $3.18 \pm 0.24\ \mathrm{d}^{-1}$ in the source bin, during the eight-week time interval 4 March–2 May 1986 simulations predict a double rate of $0.609\ \mathrm{d}^{-1}$. The mean number of doubles expected during the eight-week time interval is 34.1. The chance probability for observing 48 doubles obtained from these simulations is 0.031. This shows that the large number of doubles observed during this period is somewhat difficult to account for purely in terms of observed large shower rate during the eight-week time interval. This possibly represents burstlike activity from Scorpius X-1, as has been observed for several other binary sources [2].

Matano *et al.* [5] have observed an excess in the phase interval 0.15–0.20 for the 18.9 h binary period of Scorpius X-1. We have also searched for the 18.9 h binary modulation [15] in the flux from Scorpius X-1 ($P = 0.7874$ d, and $T_0 = 2442565.741$ Julian day). The phase distribution for showers observed during the time interval 4 March–2 May 1986 has shown a small excess (38 observed, 26.7 expected) in the phase interval 0.15–0.3. It is interesting that this phase interval (0.15–0.3) overlaps the phase region (0.15–0.20) where an excess was seen by Matano *et al.* [5]. A similar excess is also observed for the doubles, as 14 out of 48 doubles have their phase in the interval 0.15–0.30. These observations suggest that the phase interval 0.15–0.30 could be a preferred region of emission of UHE flux from Scorpius X-1.

In conclusion, we have shown that there was a significant enhancement in the flux of showers from the direction of Scorpius X-1 during an eight-week time interval, 4 March–2 May 1986. The flux observed during this period was $(6.4 \pm 1.6) \times 10^{-12}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at energies $> 2.5 \times 10^{14}$ eV. A similar enhancement has been observed in the double rate, suggesting that a part of the UHE emission was in the form of short-duration bursts lasting a few tens of minutes. A further study of emission from Scorpius X-1 is in progress at the present with a new 90-detector array at Ooty. A study of the muon content of showers due to radiation from Scorpius X-1 is planned with a 200-m^2-area muon detector having an energy threshold of 1 GeV.

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ASTRONOMY
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LETTER

Letter to the Editor

Episodic emission of UHE radiation from the eclipsing binary pulsar PSR 1957+20: Ooty observations

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Received September 14, accepted October 23, 1990

Abstract: An episode of pulsed emission of ultra-high energy, $>10^{14}$ eV, radiation from the eclipsing binary millisecond pulsar, PSR 1957+20, lasting 57 minutes has been detected on January 30, 1987 using the EAS array at Ooty. Arrival times for showers observed during this burst, when folded with the 1.607 millisecond period of the pulsar, show evidence for pulsation of the episodic flux. These observations correspond to a transient flux of 8×10^{-11} cm^{-2} s^{-1} at energies > 10^{14} eV and a luminosity of 2×10^{35} ergs s^{-1}. The episode occurred near the orbital phase of Lagrange point L_4.

Key words : Cosmic rays, gamma rays, millisec pulsar, binary stars

1. Introduction

The eclipsing binary pulsar (Fruchter et al. 1988a), PSR 1957+20, is a unique astrophysical object consisting of a 1.6 ms radio pulsar and a very low mass (0.02 M_o) companion. The binary orbital period is 9.17 h and the radio emission is completely eclipsed by the companion star for about 50 minutes. The companion star has been identified as a degenerate hydrogen dwarf from its optical emission (Djorgovski and Evans 1988, Fruchter et al. 1988b, Kulkarni et al. 1988, van Paradijs et al. 1988). An interesting scenario (Graham-Smith 1988, Kluzniak et al. 1988, Phinney et al. 1988, van den Heuvel and van Paradijs 1988) has been proposed for the evolution of this system where the optical emission has been suggested to be due to reprocessing of the incident high energy radiation from the pulsar in the environment of the companion star resulting in ablation of the low mass companion over a relatively short period of 10^8 years. This scenario suggests this pulsar to be a potential source of ultra-high energy (UHE) photons which could be produced when the beam of particles accelerated by the pulsar interacts with the target provided by the atmosphere of the companion or its stellar wind. Being a nearby source with an estimated distance of only 0.8 kpc, PSR 1957+20 is a potentially detectable source of UHE radiation since its estimated rotational energy loss rate, 10^{36} ergs s^{-1}, is very large. It has been suggested (Shapiro and Teukolsky 1988) that the emission is likely to occur at an orbital phase around the Lagrange points L_4 and L_5. We report here the results of our search for flux of UHE radiation from PSR 1957+20 from an analysis of data collected with the extensive air shower (EAS) array at Ooty during 1984-87. Evidence is presented for detection of episodic pulsed flux of UHE radiation. The episode lasting about 57 minutes was detected on January 30, 1987 at UT 5.13 - 6.10 hrs.

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2. Experimental details and data analysis

Data have been collected with the 24 scintillation detector EAS array operating at mountain altitude (2200 m) laboratory at Ooty ($11^o.4$ N) in India from June 1984 to May 1987. All showers recorded during this period have been analysed for arrival direction, core location, age and shower size. A total of 6.9×10^6 showers constitute the final database for studies on ultra high energy emission from various astrophysical sources. Details of the experimental system, trigger logic, data acquisition and analysis procedures have been summarised elsewhere (Tonwar et al. 1985, Tonwar 1985, Tonwar et al. 1988, Gupta et al. 1990). Minimum shower size recorded at Ooty with reasonable efficiency from the direction of PSR 1957+20 is 2.0×10^4 particles corresponding to an energy threshold of 10^{14} eV. The arrival time of each shower is recorded to a precision of 0.1 ms and is known to an absolute accuracy (UTC) of 0.5 ms. The angular resolution of the array has been estimated (Tonwar 1985) to be $1^o.5$. Therefore a $4^o\times4^o$ bin in right ascension (RA) and declination (DEC) centred on PSR 1957+20 (RA_{86} = $299^o.8$, DEC_{86} = $20^o.8$) has been designated as the source bin. The other 89 bins of same size and at same declination but shifted successively by 4^o in RA are used for estimating the background during the search for steady flux from the pulsar. An angular region spread over $12^o\times12^o$ and centred on the pulsar, but excluding the source region as defined above, provides eight bins, each $4^o\times4^o$, which encircle the source bin. These eight bins are used for obtaining concurrent information on the background when searching for pulsed flux.

3. Results

3.1 Search for steady flux

During the entire observation period of nearly three years PSR 1957+20, a total of 4295 showers were observed in the source bin compared to the expected background of 4303, the latter number obtained by averaging over all 90 RA bins. Also no significant excess was observed when selection was made on older (age > 1.1, Tonwar et al 1988) showers. These observations have been used to place a 99% confidence level (CL) upper limit of 4×10^{-13} cm^{-2} s^{-1} on time averaged steady flux from PSR 1957+20.

3.2 Search for flux modulated with the binary period

We have also searched for modulation in the flux of showers observed from the direction of PSR 1957+20 with the binary period of 9.167194 hours. For this purpose, the observed times (UTC) for all showers in the source bin were reduced to the arrival times at the solar system barycentre using the MIT PEP-311 program. The histogram (figure 1) of binary phase values for all showers in the source bin collected on 'good' days shows no evidence of any excess in any specific phase interval. A 'good' day was defined as a day when the observation on PSR 1957+20 lasted for 320 m as the source moved sidereally from 40° east to 40° west. A total of 682 days satisfied this criterion. Ooty observations therefore do not support results presented by Sinha et al. (1990) from observations with the EAS array at KGF which suggested emission of UHE radiation by the pulsar during the eclipse phase in the binary orbit. It should be emphasized here that Ooty and KGF arrays are located geographically very near to each other (within 300 kms) and that there is a complete overlap between observation periods for PSR 1957+20 at the two sites. The upper limit (99% CL) on the flux modulated with the binary period, obtained from Ooty data, is 1.6×10^{-13} cm^{-2} s^{-1}, assuming 10% duty factor.

3.3 Search for episodic flux

Recently we have reported (Gupta et al 1990, Tonwar et al 1990) evidence for episodic emission at UHE energies from Her X-1 and Cyg X-3 using a search program that looks for days with significant excess of events in the source bin. We have searched for episodic emission from PSR 1957+20 using a similar approach. For this purpose, data collected during 'good' days only were considered for further analysis to avoid any systematics. The average shower rate in the source bin is 5.14 per 'good' day. The distribution of number of showers per 'good' day, which extends from 0 to 14, is found to be fully consistent with expectations from Poisson distribution, except for a small deviation at the higher end. Data show 3 days with 14 showers each against the expected number of 0.62 days. The chance probability for this deviation is 2.5%.

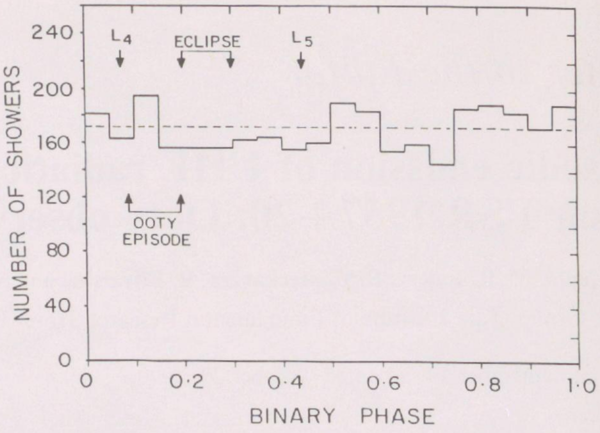

Fig. 1. : Distribution of binary phase for showers in the source bin centred on PSR 1957+20. The background is shown by the dashed line. The eclipse region, Lagrange points L_4 and L_5 and the Ooty episode are shown by the arrows.

Since several short duration episodes lasting from few minutes to few tens of minutes have been reported in the literature (Weekes 1988), including the 13 minute burst from Cyg X-3 observed (Tonwar et al. 1990) at Ooty in June 1985, we have also searched for short duration enhancements in observed shower rates from the direction of PSR 1957+20. Since the average of the observed shower rate per 'good' day in a source bin is small (about 5) for most sources studied with Ooty array during 1984-87, the probability of observing two events within 15 m of each other is less than about 25%. Therefore we have used the inter-event time interval of 15 m as a criterion to study possible short duration bursts and studied the frequency of occurrence of 'double' events, that is, pairs of events which occur within 15 m of each other. It should be emphasized here that the selection of 15 m as the time interval for 'double' event was chosen a priori from considerations of observed rates and not for optimizing any signal for any source. A look at the data for the bin centered on PSR 1957+20 with this criterion has revealed an interesting episode. While the average number of 'double' events per day is 1.24, it was observed that eight 'double' events occurred on January 30, 1987. The probability for this fluctuation to occur by chance is only 3% assuming that Poisson distribution is a good approximation for 'double' events. A closer examination of data for this day, which was one of the three days with 14 showers each, revealed that 10 of the 14 showers and all the 8 'doubles' occured within a short time duration of 57 m between 05:13 and 06:10 UT, indicating the possible detection of a burst of PeV radiation from the pulsar. The observed shower rate is a sensitive function of the zenith angle of the source. The chance probability for observing 10 showers in 57 m has been determined from mean shower rate (1.30) which has been obtained from observations on other 681 days over the same hour angle range as spanned by PSR 1957+20 during this 57 m episode. Therefore the Poisson probability for observing 10 showers in 57 m purely from statistical fluctuations, during the entire observation period, is very small;

$$P(>10,1.30) \times 682 = 1.17\times10^{-6} \times 682 = 8.0\times10^{-4}$$

This probability should be multiplied by an additional factor of 3 to take into consideration the possibility that such an episode could have occurred in any 57 m interval in the 180 m time duration when the hour angle of the source was between $22^{\circ}.5$ E and $22^{\circ}.5$ W. These limits on hour angle provide approximate bounds to the angular region where the shower rate is approximately constant and is also the largest. The probability for such an episode to be generated by random fluctuations would be much smaller at larger angles due to rapid decrease in mean shower rate.

A more realistic estimate for the chance probability of observing 10 events within a time span of 57 m in 682 observations, each of 320 m duration, has been obtained through detailed Monte Carlo simulations. The zenith angle dependence of shower rate determined using the entire Ooty database was used for these simulations. The number of showers for each trial 'good' day were generated from a Poisson distribution with a mean of 5.14 showers per day. These showers were assigned zenith angles based on the observed zenith angle distribution. The zenith angle of each shower is then converted into the hour angle of PSR1957+20. Finally the hour angle is converted into arrival time. The arrival times are then sorted in ascending order during the trial 'good' day. From these simulations the frequency of occurrence of 10 showers within 57 m anywhere during the trial 'good' day for days with $\geq$14 showers is determined. Simulations give the probability for observing such a burst by chance as $4.6 \times 10^{-6} \times 682 = 3.1 \times 10^{-3}$. This probability is slightly larger than the probability of 2.4×10^{-3} computed above which specifically required that the episode be observed when the hour angle of the source is between $22^{\circ}.5$ E and $22^{\circ}.5$ W.

3.4 Search for modulation in episodic flux with pulsar period

Arrival times of the 14 showers observed from the direction of PSR 1957+20 have been folded modulo the pulsar period, after reducing them to the solar system barycentre and correcting for the binary motion of the pulsar, for detection of the pulsar signature in the episodic flux. For this purpose, a constant value of 1.607 401 71 ms has been taken for the period. Since the magnitude of the first period derivative $(1.61\pm0.09) \times 10^{-20}$, is very small, no significant smearing of the signal is expected over the short duration (57 m) of the burst. Figure 2a shows the distribution of phase for all 14 showers. Phase distribution for the 10 showers belonging to the burst is shown separately in figure 2b. It is seen that 8 of the 10 showers of the burst cluster together conspicuously in the phase region 0.3 - 0.6.

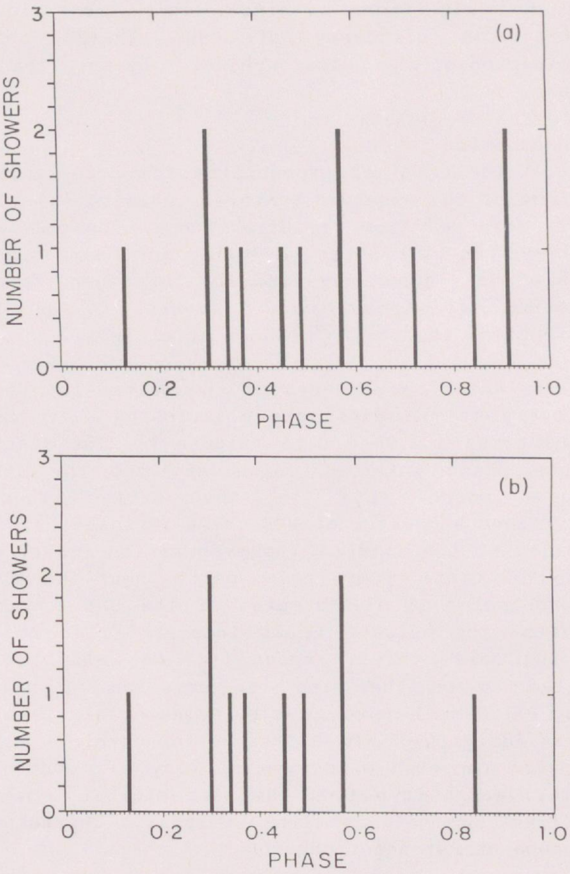

Fig. 2. : Phase distribution for showers observed on January 30,1987 from the direction of the pulsar PSR 1957+20 : (a) all 14 showers, and (b) only 10 showers observed during the 57 m duration burst.

The statistical significance of the apparently non-uniform distribution of burst events seen in figure 2b has been estimated by two different and independent methods. In the first method, the computed value (2.8) of Rayleigh power for the distribution shown in figure 2b has been used to assign it a probability of 6% for being consistent with uniform distribution. In the second method, a probability value of 1.8% has been computed from simulations requiring observation of the observed clustering of 8 out of 10 random showers.

It should be mentioned here that since the arrival time of the shower has been recorded to a precision of only 0.1 ms in the experiment there is a maximum truncation error of 6% for the 1.6 ms period of PSR 1957+20. This error is a substantial fraction of the observed duty cycle of 11% RMS (figure 2b). The effect of truncation error on duty cycle as well as the Rayleigh power, studied through Monte Carlo simulations, is found to be insignificant. The absolute phase of UHE emission in the light curve (figure 2b) does not have any significance since this detection predates the discovery of PSR 1957+20 and determination of the pulsar ephemeris by more than one year.

4. Discussion

The combined probability for occurrence by chance of the observed features, namely, (a) 10 showers detected from the direction of the pulsar within a 57 m time interval during an observation period of 682 'good' days and (b) the non-uniform clustering of these burst events in phase distribution, is 1.8x10^{-3} (Eadie et al.1971).

The binary phases of the pulsar for the 10 showers of the burst are distributed over the phase interval, 0.08 - 0.18 (figure 1). The start of this phase interval coincides with the 4th Lagrange point (L_4) in the orbit. These observations suggest that UHE gamma rays are being generated at the site of the evaporation (Shapiro and Teukolsky 1988) of Trojan matter near the 4th Lagrange point by the dumping of the UHE proton beam from the pulsar. It is interesting to note that the same orbital region (L_4) has also been reported to be the site for emission of high energy (>100 MeV) gamma rays by Brink et al.(1990) from an analysis of COS-B data. Brink et al.(1990) have also reported detection of very high energy (>2 TeV) gamma rays from the same orbital region (L_4) from observations with Atmospheric Cherenkov Telescope at Potchefstroom.

The observed flux of 10 showers within a time interval of 57 minutes corresponds to a transient flux of 8 x 10^{-11} cm^{-2} s^{-1} at energies > 10^{14} eV and the corresponding transient luminosity is 2 x 10^{35} ergs s^{-1}, assuming isotropic emission. This large energy output in UHE gamma rays over a short time interval is a substantial fraction of the rotational energy loss rate of the pulsar.

5. Conclusions

We have observed 14 showers from the direction of the eclipsing binary pulsar PSR 1957+20 against an expected average of 5.14 on three days during the three year period, June 1984 - May 1987. On one of these days, January 30, 1987, it was noticed that 10 of the 14 showers arrived within a time span of 57 m against an expected average of 1.3. Phase analysis of the arrival times for these 10 showers using the 1.6 ms period shows a significant clustering in a narrow phase interval. The binary orbital phase for the start of this episode is at the fourth Lagrange point L_4. This very nearly coincides with the region of emission of high energy (>100 MeV) and very high energy (>2 TeV) gamma rays. The probability for observing these features by random fluctuations is found to be small $\sim 10^{-3}$, after taking into consideration all degrees of freedom. Therefore we regard this burst of showers to be related to the pulsar PSR 1957+20 and consider it as evidence for episodic emission of UHE radiation from this pulsar. More observations by other groups of similar episodes of pulsed emission from PSR 1957+20 are required to establish firmly this pulsar as another UHE source, such as Cyg X-3 and Her X-1. Further observations of emission of high energy photons correlated with Lagrange points would be helpful in understanding the emission mechanism.

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