90

226

Nuclear Physics B (Proc. Suppl.) 14A (1990) 226–234
North-Holland

NEW RESULTS FROM OOTY EAS ARRAY FOR COSMIC SOURCES AT PeV ENERGIES : CYGNUS X-3, CRAB PULSAR AND SCO X-1

S.C. Tonwar, S.K. Gupta, N.V. Gopalakrishnan, M.R. Rajeev,
R. Srivatsan, and B.V. Sreekantan

Tata Institute of Fundamental Research
Homi Bhabha Marg, Colaba, Bombay-400 005, India

Ooty group has reported detection of a steady signal from Cyg X-3 based on observations made during 1984-86 through detection of a directional excess. Further analysis of data has revealed a significant flux enhancement during April 1986, confirming observations reported by the CYGNUS group at Los Alamos and the Baksan group. These results show conclusively that the flux from Cyg X-3 is variable over a time scale of few weeks. We also report here the details of an unusual burst from Cyg X-3, consisting of 5 showers in 13 minutes, on June 19, 1985, which shows the variability of the flux from Cyg X-3 on a much shorter time scale of few minutes. Our analysis of showers arriving from the direction of the Crab pulsar has shown only a small time-averaged excess. But these data, when folded with the Crab pulsar period, show a very significant excess at the expected phase of the optical interpulse. This is the first detection of 33 ms pulsation in the PeV energy flux from the Crab pulsar. The exact alignment of the phase of emission over nearly 20 decades of energy, from meter wavelengths to PeV, makes the Crab pulsar a really unique source to study and understand details of mechanisms for emission and acceleration of particles in compact sources. We also present here a discussion of our observations on another x-ray binary, Sco X-1. Ooty data show a very significant excess in the number of showers from the direction of Sco X-1 during a two month period in 1986, in agreement with observations reported by the Mt. Chacaltaya group. These observations establish this x-ray binary as another important source of PeV energy radiation.

1. INTRODUCTION

Since the 1983 report of the Kiel group[1] on detection of an excess flux of air showers of energy $>10^{15}$ eV from the direction of Cyg X-3 and the observed modulation of this flux with the 4.8 h period which is characteristic of this x-ray binary, several groups[2-4] have attempted to study Cyg X-3 and other sources at ultra-high (UHE) energies, 10^{14}-10^{16} eV. We have recently reported[5] detection of a steady flux from Cyg X-3 at energy $>2.5\times10^{14}$ eV from observations made with the EAS array operating at Ooty. This flux has also been observed to be modulated with the 4.8 h period with a significant excess in the phase interval 0.60-0.75. Observations by several groups[6-8] have suggested a significant level of variability in the flux from Cygnus X-3 at PeV energies over various time scales, particularly during 1985-86. We report here strong evidence from Ooty data for enhancement in flux from Cyg X-3 during March-April 1986 which confirms observations reported by the Baksan group[7] and the CYGNUS group[8] at Los Alamos. We also present here a discussion of Ooty observations on pulsed emission from the Crab pulsar which shows a significant phase correlation with optical

0920-5632/90/$03.50

interpulse. Finally we discuss our results for one of the brightest x-ray binaries, SCO X-1, which confirm it to be a source of PeV radiation as suggested earlier by observations with SYS array at Mt.Chacaltaya (Matano et al[9]).

2. OBSERVATIONS

Data have been collected with the 24 scintillation detector array operating at the mountain altitude laboratory at Ooty ($11^{o}.4$ N latitude, 2200 m altitude) in southern India during June '84 - May '87 All showers have been analyzed for arrival direction, core position, age and shower size. A total of 6.9×10^{6} showers constitute the final database for studies on emission of PeV energy radiation from various interesting astrophysical objects. Details of the experimental system, trigger logic, data acquisition and analysis procedures have been presented elsewhere[10]. The effective shower size threshold for the Ooty array is 5×10^{4} corresponding to an energy threshold of 2.5×10^{14} eV for showers arriving from zenith angles larger than $29^{o}.4$, which is the angle for Cyg X-3 at Ooty at meridian transit. The energy threshold for showers observed from directions close to Sco X-1 is also same but it is slightly lower, 2×10^{14} eV, for observations on the Crab pulsar. The angular resolution of the array has been estimated to be $1^{o}.5$ for showers of size $>5\times10^{4}$ from a comparison of two symmetrical sub-arrays formed out of the complete array, both in right ascension (RA) and declination (DEC). Therefore a $4^{o}\times4^{o}$ bin in RA and DEC, centered on a suspected source is designated as the source bin for all studies on this source. The other 89 bins of same size and at the same declination but shifted successively by 4^{o} in RA are used for estimating the background.

3. RESULTS

Ooty data have been examined for evidence of steady as well as pulsed flux over various time scales from several x-ray binaries (Cyg X-3, HerX-1, Sco X-1, Cyg X-1, etc.) and pulsars (PSR 0531, PSR 1913, PSR 1937, PSR 1953, etc.). However, we discuss here our observations on Cyg X-1, Sco X-1, and the Crab pulsar only.

3.1. CYGNUS X-3

Ooty group has reported[5] observing a time-averaged excess flux of $(7.16\pm3.15)\times10^{-13}$ cm^{-2} s^{-1} at energies$>2.5\times10^{14}$ eV from Cyg X-3 during 1984-86. The signal stands out more prominently among 'older' showers, confirming observations by the Kiel group[1]. However, observations made by the groups working at Baksan[7] and Los Alamos[8] during the overlapping period in 1986 have not revealed an overall excess comparable with flux observed at Ooty. Alexeenko et al[7] have reported observing the most significant excess from the direction of Cyg X-3 during the month of May 1986. Dingus et al[8] have observed a signal from Cyg X-3 only during a short period of 45 days, beginning on April 17, 1986. Both the groups have observed the 4.8 h modulation with a significant excess in the phase region, 0.60-0.75. It is possible to reconcile all these observations with each other with the hypothesis that the PeV energy flux from Cyg X-3 is variable and that the emission takes place mostly in bursts with durations lasting from few tens of minutes to few days.

We have examined Ooty data for CygX-3 over various time scales for a direct comparison with other[6-8] observations. Due to the relatively small collection area for the Ooty array and the large zenith angle for Cyg X-3 at Ooty, the average rate for the number of showers observed per 'good' day for the Cyg X-3 bin is only 1.56. A 'good' day for this purpose is defined as a day on which the observations on Cyg X-3 lasted for full 240 minutes as the source moved from east to west (zenith angle $<40^o$). This low rate does not permit a study of day to day variation. The variation of the number of events for consecutive time intervals of 7 'good' days during 1984-87 is shown in fig.1a. Note that a period of 7 'good' days does not necessarily consist of 7 consecutive calendar days as there are occasionally shorter runs in between caused either by instrumental or electrical power failures. Fig.1b shows the variation of event rate for 14 'good' day time intervals. Note the significant increase in event rate during Mar.- Apr.1986 with 55 and 47 showers observed during periods, Mar.1 -Apr.3, and Apr.4 -May 4 respectively, against the expected average of 37.5. The chance probability of observing 102 showers during March 1 - May 4, 1986, when the expected number was 75, is only 1.75×10^{-3}. It is interesting that this episode of higher shower rate at Ooty occurred so close to the period (April-May 1986) during which the other two groups[7,8] detected a signal from Cyg X-3.

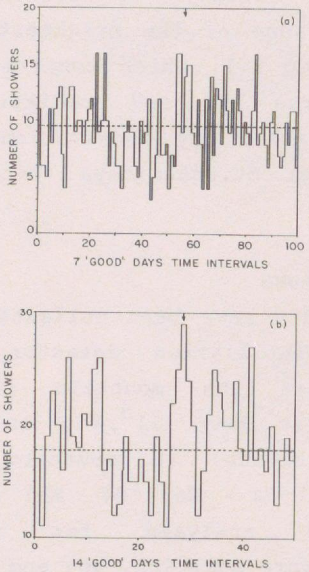


FIGURE 1
Variation of shower rate with time during the observation period, June 1984 - May 1987 ; (a) shower rate for 7 'good' days, and (b) shower rate for 14 'good' days. Arrow marks the bin starting on April 4, 1986.

Since observations[3] at TeV energies have reported flux enhancements over time intervals as short as 15 minutes, we have also attempted to detect shorter periods of flux enhancements by studying occurrence of DOUBLE events. A DOUBLE event is defined as a shower in the source bin which is followed by another shower within 15 m. The plots of the number of DOUBLE events observed in 7 and 14 'good' day time intervals are shown in fig. 2a and 2b respectively. The enhancement in the frequency of occurrence of DOUBLE events during the period, Apr.4 -Apr.19, 1986 is clearly seen in these figures. Fig.2b shows that 10 DOUBLE events have occurred during this period against an expected average number of 1.62 (chance probability 8×10^{-6}). These observations conclusively

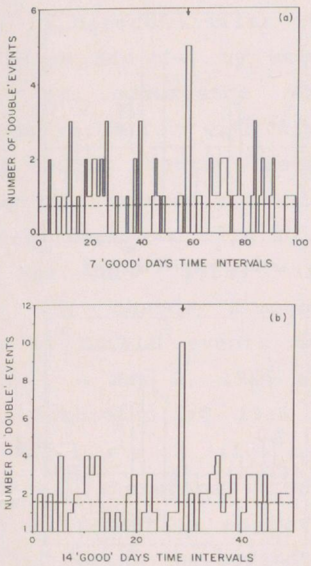


FIGURE 2
Variation of 'DOUBLE' event rate with time during the observation period, June 1984 - May 1987 ; (a) DOUBLE event rate for 7 'good' days, and (b) DOUBLE event rate for 14 'good' days. Arrow marks the bin starting on April 4, 1986.

establish that the flux of radiation from Cyg X-3 at PeV energies was significantly larger during April-May 1986 and that it is varying with time.

During this search for DOUBLE events we have also found an unusual occurrence of 5 showers (Table 1) within a short time interval of about 13 m on June 19, 1985. Since the average number of events expected in 13 minutes, assuming uniform time distribution, is only 0.0726, the chance probability for seeing 4 events within 13 m of an event is negligible (1.09×10^{-6}). With a total of 1237 events in the source bin, the overall probability is only 1.35×10^{-3}. Further, it should be noted that the age of each of the 6 events is 1.1 or larger and that 1.1 is the median value of the age for all showers observed at Ooty. The average number of such showers expected in a time interval of 13 m is only 0.0445 and there are a total of 570 such showers in the source bin. Therefore the probability of observing 4 showers of age >1.1 following a shower of age >1.1 is only $1.58 \times 10^{-7} \times 570$, that is 9×10^{-5}. Clearly, this burst is associated with the source Cyg X-3.

TABLE 1
Characteristics of showers observed at Ooty on June 19, 1985

Time (UT)	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

It is interesting to note here that this burst was observed at Ooty within 36 hours of an episode of enhanced flux observed by the Fly's Eye group[6] on June 17, 1985. Among the events seen at Dugway, the excess of events in the 4.8h phase bin centered on the value close to 0.0 was striking. Events shown in Table 1 also have phase close to 0.1, rather than 0.6-0.7 where one sees the excess for the steady flux from Cyg X-3. The flux during the short time interval of this burst is obviously much larger, almost by 2 orders of magnitude, compared to the time averaged flux observed at Ooty.

3.2. SCORPIUS X-1

Variability of the flux at PeV

energies over time scale of few weeks, as discussed above for Cyg X-3, has also been suggested for another x-ray binary, Sco X-1, by the results obtained by Matano et al[9] with the SYS array at Mt. Chacaltaya. They have observed a significant excess in the number of hadron-less showers arriving from within 7^{o} of Sco X-1 during May 1986. Among the EAS arrays operating in the northern hemisphere, only the arrays at Ooty and KGF have the capability to observe this southern source.

The number of showers observed in the source bin centered on Sco X-1 is 1700, consistent with the expected background of 1693, over the entire database. These numbers refer to showers satisfying the following selection criteria:(a) shower size > $5\mathrm{x}10^{4}$, (b) core distance from the centre of the array < 30 m, and zenith angle < 40^{o}. The excess in the source bin increases (829 vs 801 or 1.0σ) with selection of showers with age > 1.1 but not significantly. Therefore a 99% CL upper limit of $5.3\mathrm{x}10^{-13}$ cm^{-2} s^{-1} has been placed on the time averaged steady flux from Sco X-1 at energies > $2.5\mathrm{x}10^{14}$ eV for the entire observational period.

We have also examined Ooty data for presence of signal from Sco X-1 over shorter time scales. The average rate for the number of showers observed per 'good' day is only 2.13 for the source bin. During 1984-87, there were 897 days of observations on Sco X-1. However, only 771 days were 'good' days. We have examined the data over 30 'good' day intervals to compare our observations with those reported by Matano et al. Note that a period of 30 'good' days does not consist of 30 consecutive calendar days. Fig.3a shows the variation of the number of events for consecutive time intervals of 30 'good' days. Two consecutive 30 day intervals (Mar.1 - Apr.2 and Apr.3 - May 2, 1986) show a significantly larger number of showers compared to the expected background. A total of 186 showers have been observed in the source bin during this 60 'good' day period compared to the expected number of 127. The chance probability for observing this excess (5.2 σ) so close to the period of similar observation by Matano et al is very small, $5.6\mathrm{x}10^{-7}$. Since there are a total of 24 intervals of 30 'good' days, the chance probability for observing such an excess over the entire database is also quite small, $1.3\mathrm{x}10^{-5}$. Since significant enhancement of flux from Cyg X-3 over time intervals as short as 15 m

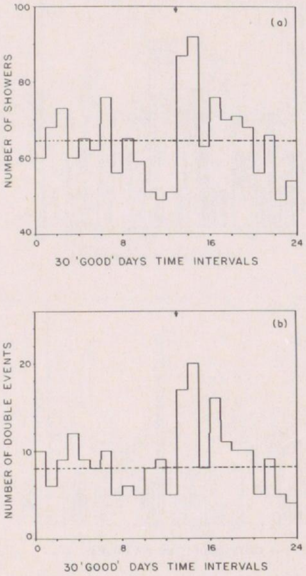


FIGURE 3
(a) Variation of the number of showers observed over 30 'good' day time intervals during June 1984 - May 1987. (b) Variation of the number of DOUBLE events observed over 30 'good' day time intervals during the same period.

has been observed by us, we have attempted to detect similar pattern in the flux from Sco X-1 by studying the frequency of occurrence of DOUBLE events. The variation with time of the number of DOUBLE events observed in 30 'good' day intervals is shown in fig.3b. The excess seen in fig.3b for the period, Mar.-June 1986, is rather striking. The chance probability of observing 49 DOUBLE events during the period Mar.1 - May 2, 1986 against an expected background of 19.8 is again very small, 2.3×10^{-8}. These observations, therefore, confirm the detection of radiation at PeV energies from Sco X-1 during the period March-May 1986. The flux at energies $>2.5 \times 10^{14}$ eV during March-April 1986, estimated from the excess seen in fig.3a is $(2.41 \pm 0.31) \times 10^{-13}$ cm^{-2} s^{-1}.

3.3. CRAB PULSAR

There have been many attempts to detect radiation from the Crab pulsar/nebula at TeV and PeV energies. There are several reports[3] of detection of steady/pulsed flux at TeV energies but most of these are based on observations spread over only few hours to few days. However, some of these observations have shown the pulsed component of the flux to be in phase with the optical main and/or interpulse. Only very recently the Whipple group[11] has succeeded in detecting radiation from the Crab pulsar/nebula over a long period of time at almost constant intensity, thanks to the success of the imaging technique[12]. Surprisingly, most of the flux detected by Weekes et al[11] seems to be unpulsed with an upper limit of 25% placed on the pulsed component.

At higher energies, 10^{14}-10^{16} eV, the Lodz[13] and the Tien-Shan[14] groups have reported detection of radiation from the direction of Crab pulsar/nebula from EAS data taken over many years. Dzikowski et al[13] detected the signal using the database accumulated by the Lodz EAS array between 1968 and 1971 and between 1975 and 1979. The signal was seen to be more prominent among muon poor showers. However, due to the poor angular resolution of the array and binning of data in $37^{\circ}.5$ in RA, association of the observed excess with the Crab nebula could be considered somewhat speculative. For data taken at Tien Shan during 1974-82, the angular resolution was such that data could be sorted into bins 15° wide in RA. With well-measured showers incident within 7 m of the centre of the array, Kirov et al[14] have reported observing a nearly 4 σ excess from the direction of the Crab pulsar/nebula among muon-poor showers. The only other positive reports[15,16] for detection of PeV energy radiation from the Crab pulsar/nebula refer to episodic emission. No attempt was made to detect the modulation of the flux with the 33 ms period for the Crab pulsar in earlier experiments due to poor time-keeping and the burst of Feb.23, 1989 reported by Alexeenko et al[16] is still to be analyzed with a proper ephemeris.

At Ooty, the number of showers observed in the source bin centered on the Crab pulsar over the entire observational period (1984-87) is 3536 compared to 3460 which is the average value obtained from the other 89 background bins. The excess of 76 showers in the source bin, a fluctuation of 1.3 σ above the expected background, is not significant statistically. Selection on shower age (>1.1) does not enhance the excess relative to the background. Other selection criteria, such as a higher energy threshold, also do not lead to any significant enhancement in the excess observed in the source bin. These observations are therefore used to place a 99% CL upper limit of 7.7×10^{-13} cm^{-2} s^{-1} on the time-averaged flux from the Crab pulsar/nebula at energies > 2×10^{14} eV.

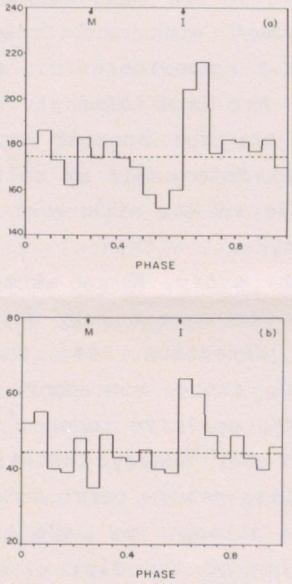


FIGURE 4
Phase histograms for showers arriving from the direction of the Crab pulsar (within ± 2° in RA and declination): (a) all showers of size > 5×10^{4} particles, and (b) only older showers with age>1.4. The arrow marks indicate the expected phases for the optical main (M) and the interpulse (I).

The occurrence time for each shower observed in the present experiment is known to an accuracy of 1 ms in absolute time (UTC), permitting a search for pulsed flux. The observed time for each event in UTC has been converted to the shower arrival time at the barycentre using the Lincoln Laboratory ephemeris (MIT PEP 311 Program). The pulsar phase for each shower is then computed using the Crab pulsar ephemeris[17] based on long term observations on the Crab pulsar at Jodrell Bank. The phase histogram for all showers is shown in fig.4a. and for old showers (age>1.4) only in fig.4b. The expected phases for the optical pulses, main and interpulse, are marked in these histograms. It is very significant that the peaks seen in both of these histograms are coincident with the expected phase of the optical interpulse. In the 20 bin plot shown in fig.4a, there are a total of 420 showers in phase bins 13 and 14 against the expected number of 347 showers. This excess (3.9 σ) has a probability of only 8×10^{-5} for occurring by chance in bins 13 and 14 coincident with the expected phase of the interpulse. Similarly, the excess (3.8 σ) seen in phase bins 13 and 14 shown in fig.4b for older showers has a probability of only 2.2×10^{-4} to occur by chance. Of course, showers used for the plot shown in fig.4b are a sub-set of showers used for fig.4a and do not constitute an independent data set. The chance probability of the peak seen in fig.4a is quite small, $20\times8\times10^{-5}$ or 1.6×10^{-3}, even if the fact of its being coincident with the expected phase of the interpulse is ignored. It is also interesting to note that though older showers (age>1.4) constitute only 25% of the total data sample in the source bin, the excess in phase bins 13 and 14 goes down only by about 50% when selection is made on larger value of age. The 73 events excess in phase bins 13 and 14 constitutes 2.1% of the total flux in the source bin for all showers. However, for older showers, this fraction is 4.0%.

Using the observed excess of 73 events contained in the interpulse region of the phase histogram (fig.4a), the pulsed flux from the Crab pulsar at energies > $2\text{x}10^{14}$ eV is estimated to be $(4.1\pm1.2)\text{x}10^{-13}$ cm^{-2} s^{-1}. This flux value is comparable to the steady value, $(2.8\pm0.8)\text{x}10^{-13}$ cm^{-2} s^{-1} reported by Kirov et al at energies $>3.5\text{x}10^{14}$ eV. However, it is much smaller compared to the value expected from extrapolation of the flux of $2\text{x}10^{-13}$ cm^{-2} s^{-1} at energies $>10^{16}$ eV given by the Lodz group.

This observation of pulsed flux from the Crab pulsar at PeV energies has far reaching implications for models for emission and acceleration of particles in pulsar magnetosphere, requiring acceleration of protons/ions to energies as high as 10 PeV near the neutron star.

4. CONCLUSIONS:

Showers from the database obtained from the 1984-87 run of the EAS experiment at Ooty have been analyzed to detect radiation from Cyg X-3, Sco X-1 and the Crab pulsar at PeV energies. Results obtained are : (a) A time-averaged flux, $(7.16\pm3.15)\text{x}10^{-13}\text{cm}^{-2}\text{s}^{-1}$, has been observed at energies $>2.5\text{x}10^{14}$ eV from Cyg X-3 modulated with the 4.8 h period. Conclusive evidence is presented for variability of the flux from Cyg X-3 over time scale of few minutes as well as few weeks. (b) Sco X-1 has been shown to be another important source of PeV energy flux with variability over a time scale of few weeks. During March-April 1986, a flux of $(2.41\pm0.31)\text{x}10^{-12}\text{cm}^{-2}\text{s}^{-1}$ at energies$>2.5\text{x}10^{14}$eV has been observed from Sco X-1. (c) Pulsed flux at PeV energy from the Crab pulsar has been observed for the first time. The pulsed flux, $(4.1\pm1.2)\text{x}10^{-13}$ cm^{-2} s^{-1} at energies $>2\text{x}10^{14}$ eV, is phase coincident with the optical interpulse for the Crab pulsar.

REFERENCES

1. M. Samorski and W. Stamm, Ap. J. **268** (1983) L17.
2. R.J. Protheroe, 20th ICRC, Moscow, **8** (1987) 21 ; A.A. Watson, 19th ICRC, La Jolla, **9** (1985) 111.
3. T.C. Weekes, Phys. Rep. **160** (1988) 1.
4. D.E. Nagle et al, Ann. Rev. Nucl. Part. Sci. **38** (1988) 609.
5. S.C. Tonwar et al., Ap. J. **330** (1988) L107.
6. R.M. Baltrusaitis et al, Ap. J. **323** (1987) 685.
7. V.V. Alexeenko et al, 20th ICRC, Moscow, **1** (1987) 219.
8. B.L. Dingus et al, Phys. Rev. Lett. **60** (1988) 1785.
9. T. Matano et al, ICR Report 164-88-10 (1988)
10. A.R. Apte et al, TIFR preprint (1989).
11. T.C. Weekes et al, Astrophys. J. **342** (1989) 379.
12. A.M. Hillas, 19th ICRC, La Jolla, **3** (1985) 445.
13. T. Dzikowski et al, 17th ICRC **1** (1981) 8.
14. I.N. Kirov et al, 19th ICRC **1** (1985) 135.
15. Boone J. et al, Astrophys. J. **285** (1984) 264.
16. V.V. Alexeenko et al, preprint (1989).
17. A.G. Lyne et al, Mon. Not. R. Astr. Soc. **233** (1988) 667; A.G. Lyne, private communication (1989).

THE ASTROPHYSICAL JOURNAL, 354: L13–L16, 1990 May 1

EPISODIC EMISSION FROM HERCULES X-1 AT ENERGIES GREATER THAN 10^{14} eV: OBSERVATIONS WITH OOTY EXTENSIVE AIR SHOWER ARRAY DURING 1986

S. K. GUPTA, M. R. RAJEEV, B. V. SREEKANTAN, R. SRIVATSAN, AND S. C. TONWAR
Tata Institute of Fundamental Research

Received 1989 November 13; accepted 1990 February 14

ABSTRACT

During 1986 May–July, three groups have reported detection of episodic pulsed flux from Her X-1 but with a period which was significantly smaller than the X-ray period. We have searched for similar episodes in Ooty data for 1986. Data for four days, July 1, August 8–9, and November 21, selected from days with higher than average observed shower rates, have shown evidence for flux pulsed with the same smaller period. A search for correlation between these episodes with a period precise enough to phase-lock the signal from Her X-1 has confirmed them to be related. This highly precise period, 1.2357701 s, is fully consistent with other observations during 1986. The episodic flux estimated from Ooty observations is $(3.0 \pm 0.7) \times 10^{-11}$ cm^{-2} s^{-1} at energies $>10^{14}$ eV. Significantly, the $1^{\mathrm{d}}.7$ orbital phases for showers observed in Ooty episodes show clustering near phase of 0.65, and these episodes have all occurred near phase of 0.65 during the LOW ON state of the 35^{d} cycle. A search of the Ooty data base for days with larger shower rate and at expected phase of 0.65 for $1^{\mathrm{d}}.7$ and 35^{d} modulation has revealed a fourth episode on 1986 December 27 which also shows the pulsar periodicity in phase with earlier episodes. These observations establish conclusively Her X-1 to be an episodic source at PeV energies.

Subject headings: gamma rays: general — stars: binaries — stars: individual (Her X-1) — stars: pulsation

I. INTRODUCTION

Hercules X-1 is a low-mass eclipsing X-ray binary containing a neutron star with three well-defined periodicities: 1.24 s due to the rotation of the neutron star, $1^{\mathrm{d}}.7$ due to orbital motion, and 35^{d} assumed to be due to precession of either the accretion disk or the neutron star. In 1983 April, Dowthwaite *et al.* (1984) observed a 3 minute burst of emission at TeV (10^{12} eV) energies from Her X-1 with the characteristic 1.24 s periodicity measured in X-ray flux. The Whipple collaboration (Weekes 1988) has also detected seven episodes of pulsed emission from Her X-1 during 1984–1985. The first detection of pulsed flux from Her X-1 at PeV (10^{15} eV) energies was reported by Baltrusaitis *et al.* (1985) from observation of a 40 minute duration episode on 1983 July 11. Recently, Resvanis *et al.* (1988) have reported observing a 15 minute burst from Her X-1 at TeV energies on 1986 May 13. This was followed by the observation of a 25 minute episode by Lamb *et al.* (1988). Surprisingly, both these episodes showed pulsation with an apparently anomalous period which was significantly (0.16%) smaller than the X-ray period, 1.2378 s. These observations were soon followed by the detection of a burst at PeV energies by Dingus *et al.* (1988) on July 24 which showed pulsation with the same anomalous period.

In this *Letter* we summarize the results of the search for episodes of pulsed emission from Her X-1 at PeV energies in data collected at Ooty. We have observed four well-separated episodes which show pulsed emission at a highly precise period of 1.2357701 s which is consistent, within quoted errors, with period values reported by the other three groups.

II. OBSERVATIONS

Data have been collected with the 24 scintillation detector array (Sreekantan *et al.* 1983) operating at Ooty ($11^\circ.4$ N latitude and 2200 m altitude) in southern India during 1984 June–1987 May. For each shower trigger, data on relative arrival time and particle density in each detector along with the real time (accuracy 1 ms) is recorded. All showers recorded during this period have been analyzed for arrival direction, core position, age, and shower size. A total of 6.9×10^6 showers constitute the final data base for studies on cosmic sources at PeV energies. Details of the experimental system, trigger logic, data acquisition, and analysis procedures have been discussed elsewhere (Tonwar *et al.* 1985, 1989). Minimum shower size recorded at Ooty with reasonable efficiency from the average zenith angle of Her X-1 is 2×10^4 particles corresponding to an energy threshold of 10^{14} eV. The angular resolution of the array has been estimated (Tonwar 1985) to be $1^\circ.5$. Therefore a 4° × 4° bin in right ascension (R.A.) and declination (decl.), centered on Her X-1 (R.A. $254^\circ.3$, decl. $35^\circ.4$) has been designated as the source bin. An angular region spread over 12° × 12° and centered on Her X-1, but excluding the source region as defined above, provides eight bins, each of 4° × 4°, which surround the source bin. These eight bins are used for obtaining concurrent information on the background when searching for periodicity.

During the entire observation period of 1043 days, Her X-1 was observed on 904 days. However, the taking of data was interrupted on some days due to either mains power or instrumentation failure. Therefore, data collected only on "good" days were considered for further analysis. A "good" day was defined as a day on which the observations on Her X-1 lasted for 280 minutes as the source moved from hour angle 35° east to 35° west (zenith angle <40°). A total of 685 days satisfied this criterion. Only showers with their cores incident within 30 m of the center of the array were considered for the periodicity search discussed below.

III. ANALYSIS AND RESULTS

a) Detection of Episodic Pulsed Flux from Hercules X-1 at Ooty

The episode of pulsed emission reported by Dingus *et al.* (1988) was detected using a search program which looked for days with significant excess of showers in the source bin and for an excess rate of showers during some interval of time on those days. We have followed a similar strategy. In our case the observed shower rate in the source bin is rather small, 2.48 showers per "good" day, mainly due to larger average zenith angle for the source at Ooty and smaller collection area of the array. Data for 685 "good" days shows the number of days with six, seven, eight, and greater than or nine showers to be 11, 11, two, and zero, respectively, consistent with Poisson distribution. However, a careful examination of data around the time of the Los Alamos burst revealed an interesting occurrence. On each of the two successive days, 1986 August 8 and 9, six showers were observed. Though the probability for observing such an occurrence by chance over 685 days is not very small, our attention was drawn strongly to this episode by the fact that it occurred within 17 days of the burst detected at Los Alamos. We therefore decided to subject the observed times for these 12 showers to further analysis to search for 1.24 s periodicity. The observed times (UTC) for all showers in the source bin were reduced to the arrival times at the solar system barycenter using the MIT PEP-311 program and were corrected for the orbital motion of the pulsar using the ephemeris of Deeter *et al.* (1981). Though the Rayleigh test has been used extensively in searches for periodicity, this test is relatively insensitive for narrow features in the light curve. Protheroe (1985*a*, *b*) has recently suggested a new test to search for periodicity in small data samples which has relatively higher sensitivity to narrow features. This is basically due to the fact that the statistic is defined in terms of phase separations between all pairs of events in data set. Since the duty cycle for emission from Her X-1 at PeV energies has been seen to be small, Dingus *et al.* (1988) have used Protheroe statistics, and the same has been preferred by us. Due to the spread of these showers over 30 hr, an accuracy of better than 20 μs is required in the value of the period to phase-lock the signal to within one cycle of the pulsar. Therefore a narrow period range, 1.2357–1.2359 s, around the average value of the period observed by the three groups (Resvanis *et al.* 1988; Lamb *et al.* 1988, and Dingus *et al.* 1988). was scanned in steps of 10 μs. This analysis yielded a relatively large value of 5.23 for the Protheroe statistic (PST) for the period value 1.23577 s. The chance probability for this PST value has been estimated from Monte Carlo simulations to be 1.75×10^{-3}. Allowing for 20 periods scanned, the overall chance probability is 3.5×10^{-2}. The phase distribution showed that 10 of the 12 showers observed on August 8–9 (referred hereafter as episode I) have clustered together in a narrow phase region. The chance probability for occurrence of this episode within 17^d of the Los Alamos burst is small and coupled with a significant value for the PST with a period close to the Los Alamos value (1.23568 s) suggests strongly that this episode represents pulsed emission from Her X-1.

As mentioned earlier, eight showers per "good" day were observed in the source bin only on two of the 685 days. These days are 1986 July 1, which is only 22 days before the episode observed at Los Alamos, and 1986 November 21, which is 120 days after the Los Alamos burst. Data for each of these days were also subjected to periodicity analysis at the period value of 1.23577 s found from episode I. Data for July 1, referred to as episode II hereafter, gave a value for PST corresponding to a chance probability of 2.9×10^{-2}. The PST value obtained for showers observed on November 21 (episode III) corresponds to a chance probability of 8.8×10^{-2}. Showers observed during episodes II and III show phase clustering similar to that seen for episode I. The lower limit for the chance probability for obtaining nonrandom distributions in these three apparently unrelated episodes with a period value of 1.23577 s is the product of the three probabilities, $3.5 \times 10^{-2} \times 2.9 \times 10^{-2} \times 8.8 \times 10^{-2}$, i.e., 8.9×10^{-5}. The upper limit for the chance probability can be obtained using the method discussed by Eadie *et al.* (1971). This is calculated to be 4.8×10^{-3} from a value of χ^2 of 18.65 with 6 degrees of freedom. Since the latter value of probability assumes that all values between 0 and 1 are possible for each of the three individual probabilities, it does not represent an accurate estimate for the chance probability in the present situation since a large value, say greater than 0.1, for a data set would have disqualified it as a possible episode. However, there is a subjective element involved in these assignments of probabilities, and we regard 5×10^{-4} as a conservative estimate for the chance probability for observing the 1.23577 s periodicity in data for these three episodes.

Since the three episodes are spread over 143 days, submicrosecond accuracy is required in the period to phase-lock the signal detected in these episodes. We have calculated the PST for 100 periods between 1.2357650 s and 1.2357750 s, varying period in steps of 100 ns, around the period value of 1.23577 determined from episode I, for the combined data of these episodes (total 28 showers). It is found that the period value of 1.2357701 s gives the largest value of 7.80 for the PST. The chance probability for this PST value obtained from simulations is less than 2.2×10^{-6} and the overall probability is only 2.2×10^{-4} taking into account 100 trial periods. The phase distribution for this period is shown in Figure 1. It is interesting to note that 22 of 28 showers cluster together in the phase region 0.11–0.38.

As mentioned earlier, the eight bins surrounding the source bin have data concurrent with the source bin. These eight bins have a total of 79 showers during the same time period that the source bin got 28 showers. The expected number of showers in eight background bins, based on source bin data averaged over the entire duration of the experiment, is 79.4 (4 days × 8 bins × 2.48 per day). A periodicity analysis on 28 showers, randomly picked from background showers, with period of 1.2357701 s gives a small value for PST and a phase distribution as expected from uncorrelated showers. This shows that observation of excess rate as well as 1.24 s periodicity on these 4 days was restricted to source bin only and that data taken

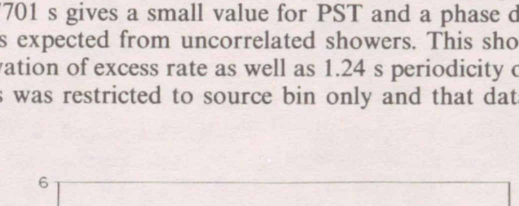
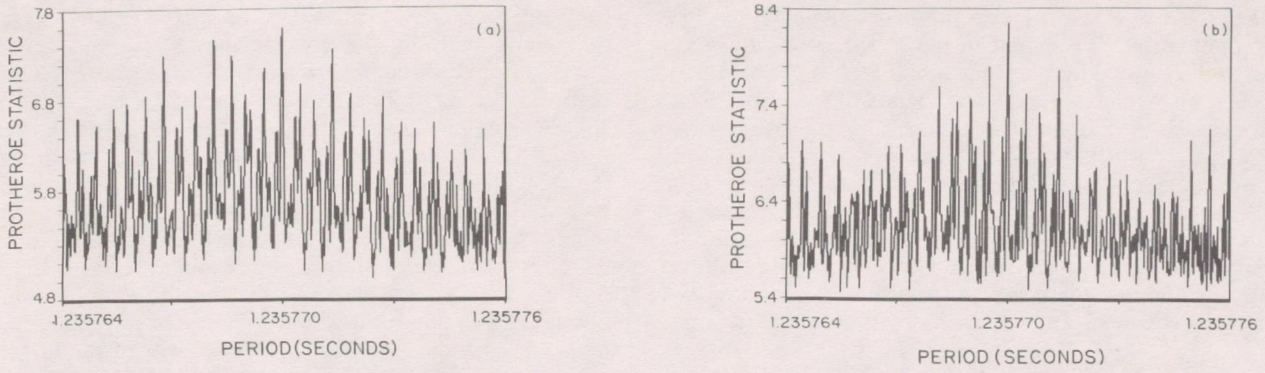


FIG. 1.—Phase distribution for showers from the source bin centered on Her X-1 observed at Ooty during the three episodes for the pulsar period of 1.2357701 s.



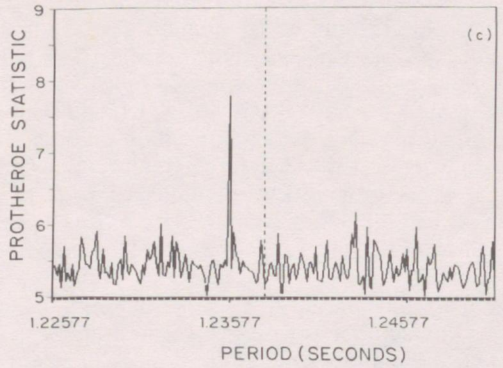


FIG. 2.—Variation of the value of Protheroe statistic with pulsar period (*a*) for 28 showers observed in the three episodes, (*b*) for 34 showers observed in the four episodes, and (*c*) for 28 showers observed in the three episodes but over a broader period range. A vertical dotted line is shown at the expected value of the X-ray period.

concurrently in nearby eight background bins shows nothing unusual.

Significant phase correlations between showers observed in the three episodes, as revealed by the preceding periodicity analysis, which led to the phase clustering of showers seen in Figure 1, are regarded by us as strong evidence for detection of episodic pulsed flux from Her X-1 at energies $>10^{14}$ eV. The episodic flux value obtained from these three episodes is $(3.0 \pm 0.7) \times 10^{-11}$ cm^{-2} s^{-1} at energies $>10^{14}$ eV. This is comparable to the value of 2×10^{-11} cm^{-2} s^{-1} estimated by Dingus *et al.* for the burst of July 24 at Los Alamos.

During the period 1986 July 1 and November 21 there are four other days, three with seven showers observed per day in the source bin and one with six showers. Data of these four days when analyzed independently with the period 1.2357701 s do not show any evidence for pulsed signal.

During the period scan discussed above, a regular structure in the distribution of PST values was noticed. We then carried out a finer scan in steps of 20 ns, and Figure 2*a* shows a plot of PST values around the period value of 1.2357701 s. It was noticed that a large value of PST was obtained whenever the period changed either by 120 ns or 460 ns. Note that the time separations between episodes I and II and between epsiodes II and III were $38\overset{\mathrm{d}}{.}37$ and $142\overset{\mathrm{d}}{.}6$, respectively. It turns out that a change of 124 ns or its multiples in the period changes the number of pulsar cycles elapsed in $142\overset{\mathrm{d}}{.}6$ by an integer number, without disturbing the relative phase values for showers within the episodes. Similarly a change of 461 ns in period changes the number of pulsar cycles elapsed in $38\overset{\mathrm{d}}{.}37$ by an integer value. Therefore changes in period which are close to 124 or 460 ns or their multiples lead to larger values of PST. However, phase distributions for the 28 showers were found to be very similar for all period values which give a large value for PST and show significant excess of showers in phase region 0.1–0.4. This degeneracy in period values can be resolved only through observation of more such episodes which would then permit determination of a unique high precision period of the pulsar at PeV energies. As discussed later in § III*d*, we have found another episode (IV) which occurred on 1986 December 27. Figure 2*b* shows the plot of PST values calculated using 34 showers which include six showers observed in the fourth episode. The decrease in period degeneracy caused by the inclusion of episode IV is clearly noticeable in this figure when compared with Figure 2*a*. It should also be mentioned here that the PST distribution, shown in Figure 2*c*, for periods significantly different from 1.23577 s was consistent with expectations from random distribution. Note that the value of the period derivative ($\dot{p}$) has been assumed to be zero during the analysis discussed above in the absence of any data on $\dot{p}$ at TeV and PeV energies. Data available here from the three episodes are not sufficient to make any meaningful statement on $\dot{p}$, and detection of many more episodes spread over many months or years is required to determine the value of the period derivative.

b) *Modulation of Episodic Pulsed Flux with 1.7 Day Binary Period*

Data for the three episodes discussed above when folded with the $1\overset{\mathrm{d}}{.}70016773$ binary period (Deeter *et al.* 1981) have shown that 22 of 28 showers cluster together in phase region 0.54–0.76. Here a phase value of 0.0 corresponds to the time of X-ray eclipse. Note that phase values for showers observed in any individual episode of duration 4 hr 40 minutes, which is the total observation time at Ooty on a "good" day, are spread over a narrow phase interval of width 0.11. The chance probability for 22 showers from the three episodes to cluster within the phase window of 0.22 is less than 5%. It is interesting to note that the 40 minute burst observed on 1983 July 11 by Baltrusaitis *et al.* (1985) also occurred at phase of 0.66. However, the burst observed at Los Alamos occurred in the region of 0.8–0.9 of the binary phase.

c) *Modulation of Episodic Pulsed Flux with 35 Day Precession Period*

The modulation of episodic pulsed flux with the $35\overset{\mathrm{d}}{.}08$ precession period (Ögelman 1987) has shown that all 28 showers cluster in the phase region 0.59–0.70 around the center (0.65) of the LOW ON state of X-ray emission. As mentioned above for the $1^{\mathrm{d}}.7$ modulation, the spread in phase values for showers observed in any individual episode is only 0.0055 for the 35^{d} period. The probability for the occurrence of observed clustering by chance is only about 1%. The episode observed by the Fly's Eye group (Baltrusaitis *et al.* 1985) also occurred at the phase value of 0.63, but the episode detected at Los Alamos, in contrast, was at the phase value of 0.23 corresponding to the HIGH ON state. It should be noted here that the 35^{d} periodicity in X-ray flux from Her X-1 appears and disappears stochastically and that there were no optical or X-ray observations on Her X-1 concurrent with episodes discussed here.

d) Predictions for Observable Episodes

The clustering observed in phase distributions for both $1^{\mathrm{d}}.7$ and 35^{d} periods suggest that the phase region around 0.65 may be a preferred region for emission of episodic pulsed flux from Her X-1 at PeV energies. We have searched the Ooty data base for days when these phase conditions are satisfied and the number of observed showers in the source bin are significantly larger (≥ 6) than the average (2.48) value. Only one such occurrence (1986 December 27) was found. A periodicity analysis on six showers observed on this day with 1.2357701 s period showed that four showers have phase between 0.17 and 0.30 which strongly suggests the observation of December 27 as the fourth episode. With the inclusion of showers observed in this episode, 26 of the 34 showers have phase in the region 0.11–0.38.

IV. DISCUSSION AND CONCLUSIONS

The occurrence of two successive days, 1986 August 8–9, with somewhat higher daily rate for showers in the source bin centered on Her X-1, provided the first possible episode for periodicity analysis. This episode showed evidence for pulsed flux at a significant level with a period very close to the average period observed at TeV and PeV energies during 1986 May–July. A search for nearby days with high observed shower rate provided the other two episodes which also showed evidence for 1.24 s periodicity. A search for higher precision in period linking these episodes led to a period of 1.2357701 s for pulsed flux from Her X-1 at PeV energies. Note that selection of these episodes had no relation to 1.24 s period as it was solely based on the criterion of large value for the shower rate. Similarly observation of phase clustering seen for the $1^{\mathrm{d}}.7$ and 35^{d} modulation in episodic flux is also independent of the larger rate selection criterion. Finally, discovery of the fourth episode, which was based on the prediction from the observed phase clustering seen for $1^{\mathrm{d}}.7$ and 35^{d} modulation for the first three episodes, does not have any relation with the 1.24 s pulsation detected subsequently. All these considerations show that no optimizing parameters have been used which could have generated the highly significant 1.24 s pulsation observed in data for these four episodes. Therefore, results discussed here confirm the earlier observations of Baltrusaities *et al.* (1985) and Dingus *et al.* (1988) and establish Her X-1 as an episodic source of pulsed radiation at PeV energies. The episodic flux of $(3.0 \pm 0.7) \times 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ at energies $> 10^{14}$ eV corresponds to an episodic luminosity of 4×10^{37} ergs s^{-1} at energies $> 10^{14}$ eV, assuming isotropic emission from the source at a distance of 5 kpc and a differential power-law energy spectrum with exponent of -2.6 which is characteristic of Galactic cosmic-ray flux.

REFERENCES

Baltrusaitis, R. M., *et al.* 1985, *Ap. J.* (*Letters*), **293**, L69.
Deeter, J. E., *et al.* 1981, *Ap. J.*, **247**, 1003.
Dingus, B. L., *et al.* 1988, *Phys. Rev. Letters*, **61**, 1906.
Dowthwaite, J. C., *et al.* 1984, *Nature*, **309**, 691.
Eadie, W. T., *et al.* 1971, *Statistical Methods in Experimental Physics*, (Amsterdam: North-Holland), p. 283.
Lamb, R. C., *et al.* 1988, *Ap. J.* (*Letters*), **328**, L9.
Ögelman, H. 1987, *Astr. Ap.*, **172**, 79.
Protheroe, R. J. 1985*a*, *Astr. Express*, **1**, 137.
———. 1985*b*, in *Techniques in Ultra-High Energy Gamma Ray Astronomy*, ed. R. J. Protheroe and S. A. Stephens (Adelaide: University of Adelaide), p. 91.
Resvanis, L. K., *et al.* 1988, *Ap. J.* (*Letters*), **328**, L9.
Sreekantan, B. V., *et al.* 1983, *Phys. Rev.*, **D28**, 1050.
Tonwar, S. C. 1985, in *Techniques in Ultra-High Energy Gamma Ray Astronomy*, ed. R. J. Protheroe and S. A. Stephens (Adelaide: University of Adelaide), p. 40.
Tonwar, S. C., *et al.* 1985, *19th Internat. Cosmic Ray Conf.*, La Jolla (NASA CP-2376), **1**, 242.
Tonwar, S. C., *et al.* 1989, TIFR preprint.
Weekes, T. C. 1988, *Phys. Rept.*, **160**, 1.

S. K. GUPTA, M. R. RAJEEV, B. V. SREEKANTAN, R. SRIVATSAN, and S. C. TONWAR: Tata Institute of Fundamental Research, Homi Bhabha Marg, Colaba, Bombay-400 005, India

J. Astrophys. Astr. (1990) **11**, 73–79

Search for High-Energy Neutrinos from SN1987A in KGF Nucleon Decay Experiments

H. Adarkar, S. R. Dugad, M. R. Krishnaswamy, M. G. K. Menon, N. K. Mondal, V. S. Narasimham, B. V. Sreekantan *Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400005*

Y. Hayashi, N. Ito, S. Kawakami, T. Nakamura, K. Tanaka *Osaka City University, Sumiyoshi-ku, Osaka 558, Japan*

S. Miyake *Kanagawa University, Rokkakubashi 3, Yokohama, Japan*

Received 1989 June 6; accepted 1989 November 4

Abstract. A search is made for high-energy neutrinos (>1 GeV) from the supernova SN1987A through muons produced in the rock surrounding Kolar Gold Fields (KGF) nucleon decay detectors. Due to the special location of the detectors near the equator, these muons appear in the detector with zenith angles $>55°$. In this angular region the contribution from normal atmospheric muons is negligibly small. No event is found within a cone of half-angle 8° around SN1987A in a live-time of $\simeq 2$ years, subsequent to the supernova burst on 1987 February 23 till 1989 March. Assuming a neutrino spectrum $E^{-2.1}dE$ and a cutoff ν-energy of 10^{12} eV, this result leads to an upper limit (90 per cent C.L.) of $1.3 \times 10^{-4}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for the neutrino flux (>1 GeV) and $3.6 \times 10^{41}\ \mathrm{erg\,s}^{-1}$ for the luminosity of SN1987A in an exposure of $\simeq 83\ \mathrm{m}^2\,\mathrm{yr}$.

Key words: supernovae, general—supernovae, individual (SN 1987a)—neutrinos—muons—kaons

1. Introduction

The supernova burst SN1987A ($\delta = -69°$, $\alpha = 5\mathrm{h}\ 35\mathrm{m}$) observed on 1987 February 23 has given clear neutrino signals of energies 10–30 MeV (Bionta *et al.* 1987; Hirata *et al.* 1987). Two other experiments (Aglietta *et al.* 1987; Alexeyev *et al.* 1987) also have reported detection of neutrinos from this burst though at different times. The neutron star produced during this explosion is expected to become a source of high-energy cosmic rays and neutrinos. There are many models for this hypothesis, some of them predicting luminosities $>10^{43}\ \mathrm{erg\,s}^{-1}$ for the high energy protons. According to these models (Cavallo & Pacini 1980; Blandfold & Ostricker 1980; Ginzburg & Ptuskin 1984; Gunn & Ostricker 1969) particles accelerated by the neutron star or by the shock wave of the explosion, produce pions and kaons through collisions with the expanding envelope from the supernova burst. The decay in flight of these pions and kaons will give high energy neutrinos. Thus, a signal of steady flux of high energy neutrinos from SN1987A will provide experimental evidence of particle acceleration in this supernova.

The search for such a steady signal of high energy neutrinos from SN1987A is continuing in many large scale experiments and an upper limit on this flux has been reported by Oyama *et al.* (1987). Here we report the search for neutrinos of energy >1 GeV from SN1987A in phase I and phase II of the nucleon decay experiments being operated at KGF (12.9°N, 78.3°E) in India.

2. The experiment and results

The KGF detectors are essentially calorimeters with alternating layers of proportional counters of wall thickness 2.3 mm and iron absorbers (Krishnaswamy *et al.* 1982, 1986). The counter layers are crossed to enable three-dimensional reconstruction of the tracks. The other relevant details of the two detectors are given in Table 1.

The basic trigger is a five-fold coincidence of any 5 layers (with at least one counter per layer) out of 11 consecutive layers. In addition there is a special 2-layer coincidence with at least 2 counters per layer to record tracks with large zenith angles. Thus the detector covers almost all the directions in space except for a narrow band between zenith angles (θ) 87° and 93°. This small gap in acceptance due to the triggering criteria is taken into account in the estimate of exposure. The trigger threshold is $\simeq 100$ MeV for both the detectors.

At such large depths the majority of events recorded are due to atmospheric muons which have a steep zenith angular distribution (Fig. 1 for Phase II) with negligible flux beyond 60°. On the other hand, the muons produced in ν-interactions in the surrounding rock are nearly isotropic so that a clear separation is possible between these two sources of muons. However, we have to restrict the angular regions to 60°–120° and 65°–115° for Phase I and II detectors respectively in view of the fact that up and down sense of motion could not be obtained due to the slow response of counters employed here. In spite of these angular cuts, as shown in Fig. 2, the source

Table 1. Specific details of the KGF nucleon decay detectors.

Description	Phase I	Phase II
Depth	2.3 km (7000 hg cm^{-2})	2.0 km (6045 hg cm^{-2})
No. of proportional counter layers	34	60
Detector size	6 m × 4 m × 3.8 m	6 m × 6 m × 6.4 m
Thickness of absorber plates (iron)	12 mm	6 mm
Angular resolution	1° for full tracks 4° for 1 m tracks	1° for full tracks 4° for 1 m tracks
Zenith angle region for this study	82°–120°	82°–115°
Live-time (1987 Feb 23 to 1989 March 29)	535 d	658 d

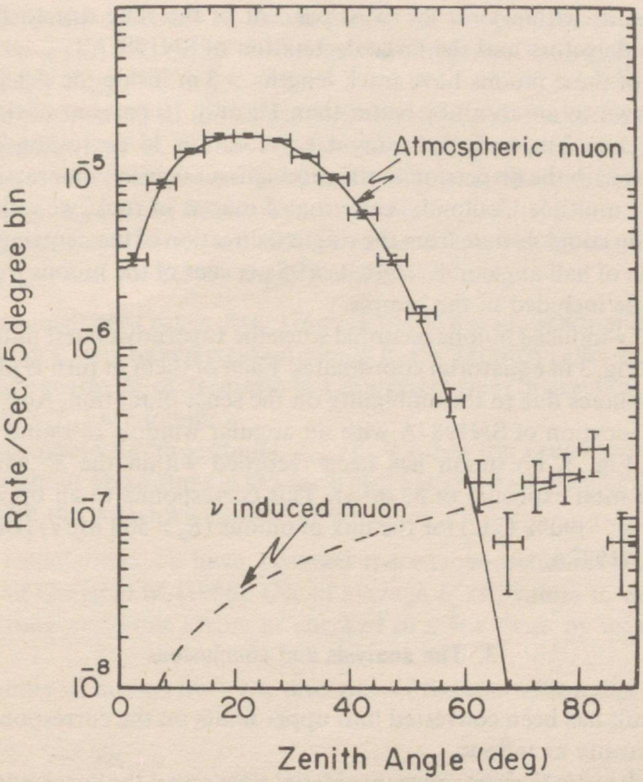


Figure 1. The zenith angular distribution of atmospheric and neutrino-induced muons in the Phase II detector at the depth of 6045 hg cm^{-2} in Kolar Gold Fields. The solid curves show the rates expected on the basis of past experiments in the case of atmospheric muons and calculations in the case of neutrino-induced muons. Beyond 65° the rate of neutrino-induced muons remains almost constant; that of atmospheric muons falls off rather steeply and is negligible. The distribution is similar for Phase I at 7000 hg cm^{-2} the cutoff angle being 60°.

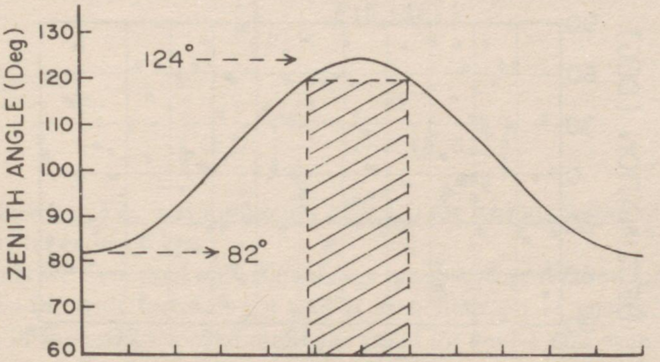


Figure 2. The zenith angle θ of SN1987A as a function of (RA – Siderial Time) at Kolar Gold Fields (12.9°N, 78.3°E). The hatched region shows the 'off-time' per 24 siderial hours. It can be seen that the source remains in the accepted angular region ($60° < \theta < 120°$) for more than 70 per cent of a siderial day.

SN1987A remains within view for >70 per cent of the time due to the equatorial latitude of the detectors and the large declination of SN1987A.

A majority of these muons have track lengths >3 m inside the detector and their angles are known to an accuracy better than 1°; only 10 per cent of the events have track lengths 1 m–3 m and their angular resolution is correspondingly poorer. Combining this with the dispersion in the production angle in ν-interactions as well as the subsequent multiple Coulomb scattering of muons in rock, we estimate that the secondary muon could deviate from the original direction of the neutrinos by $\simeq 4°$. We thus use a cone of half angle of 8° so that >95 per cent of the muons from the source direction will be included in the sample.

A total of 80 ν-induced muons recorded since the supernova burst until 1989 March are plotted in Fig. 3 in equatorial coordinates. Each of them in turn is plotted twice in the two hemispheres due to the ambiguity on the sense of motion. Also shown in this figure are the location of SN1987A with an angular window of radius 8° around it.

As seen in Fig. 3. no muon has been recorded within the 8° window around SN1987A in a total exposure of 83 m^2 yr. This corresponds to an upper limit of 8.8 $\times 10^{-14}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (90% C.L.) for the flux of muons ($E_\mu > 500$ MeV) coming from the direction of SN1987A.

3. The analysis and conclusions

The above result has been converted into upper limits on the corresponding neutrino flux and luminosity as follows.

1. The zenith angle θ of the source at siderial time t_s and the corresponding effective area $A(t_s)$ presented by the detector to the source are calculated as a function of siderial time t_s. The effect of triggering criteria and the zenith angle cut to suppress atmospheric muons are taken into account in this calculation.

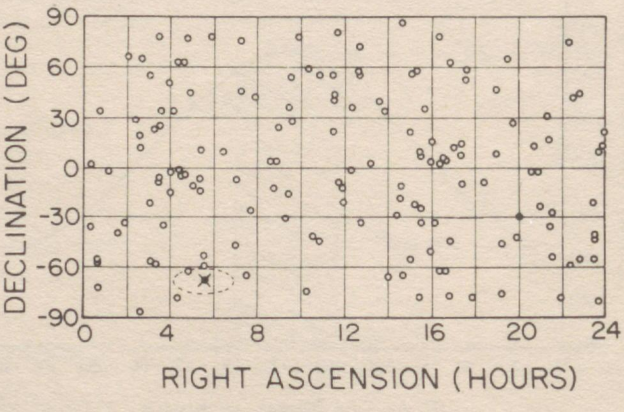


Figure 3. The celestial plot of the 80 large-angle ($\theta > 60°$) muons seen in Phases I and II of the KGF nucleon decay experiment. Since 'Up-Down' information is not available for these tracks, each event it shown twice corresponding to two opposite directions in the celestial sphere. The position (marked by a X) of SN1987A and a window of radius 8° around this source are also shown.

2. The differential spectrum of the neutrinos (ν)* at production in the source, is assumed to be $F(E_\nu)\mathrm{d}E_\nu = CE_\nu^{-(\gamma+1)}\mathrm{d}E_\nu$, the neutrinos having energies up to a maximum energy E_{cutoff}.

3. The muon produced in the charged current neutrino interaction is required to have a minimum energy of 500 MeV before entering the detector to satisfy the event selection criterion of a minimum pathlength of 1 m inside the detector. Thus the threshold energy E_{th} for the neutrino is $\simeq 1$ GeV.

4. The following quantities are calculated as a function of neutrino energy E_ν ($E_{\mathrm{th}} < E_\nu < E_{\mathrm{cutoff}}$) and the zenith angle θ of the neutrino.

(i) We define a restricted range $R(E_\mu)$ in rock of the muon such that a muon with an initial energy E_μ will have a residual energy $E_{\mathrm{th}}(=500$ MeV) after traversing $R(E_\mu)$. The average energy E_μ of the muon in a charged current interaction of the neutrino and hence $R(E_\mu)$ are found.

(ii) Next we compute the probability $P_{\mathrm{sur}}(E_\nu, t_s)$ that the neutrino from the source survives without absorption in the earth and enters a rock shell of thickness $R(E_\mu)$ surrounding the detector at siderial time t_s.

For these calculations we have assumed the ν-cross-sections $\sigma(E_\nu)$ and average E_μ/E_ν ratios of Quigg *et al.* (1986). Use of average E_μ/E_ν values to determine muon energy gives only negligible errors as checked in a few cases by using the actual y distribution.

5. The number of muons from the direction of the source entering the detector is then,

$$M = \int_0^{T_s} \int_{E_{\mathrm{th}}}^{E_{\mathrm{cutoff}}} F(E_\nu) P_{\mathrm{sur}}(E_\nu, t_s) \sigma(E_\nu) N_{\mathrm{AV}} R(E_\mu) A(t_s) \,\mathrm{d}E_\nu \,\mathrm{d}t_s$$

where T_s = Actual run-time of detector in siderial hours and N_{AV} = Avogadro number. Equating M to the number of events seen (=2.3 for 90% C.L.) will determine the normalization constant C in $CE^{-(\gamma+1)}$. From this we obtain the neutrino flux

$$\left\{ \int_{E_{\mathrm{th}}}^{E_{\mathrm{cutoff}}} F(E_\nu)\,\mathrm{d}E_\nu \right\}$$

and the luminosity

$$\left\{ 4\pi D^2 \int_{E_{\mathrm{th}}}^{E_{\mathrm{cutoff}}} F(E_\nu) E_\nu \,\mathrm{d}E_\nu \right\}$$

which are shown in Fig. 4 as a function of E_{cutoff} for various values of γ. The source distance D is taken as 50 kpc.

In this study we have used only the average range-energy relation for the muon *viz.* $-\mathrm{d}E/\mathrm{d}x = a + bE$ with increasing a and b as a function of energy. The effect of fluctuations in the energy loss of muons is small for $\gamma = 1.1$ and even for the largest γ (=1.9) the maximum contribution to muon intensity comes from the region of few hundred metres of the rock surrounding the detector; for these overburdens fluctuations are small (<10 per cent).

---

* Throughout this paper ν means ν_μ and $\bar{\nu}\mu$. We do not consider ν_e and $\bar{\nu}_e$ since they contribute only a very small and negligible fraction to the type of events considered here.

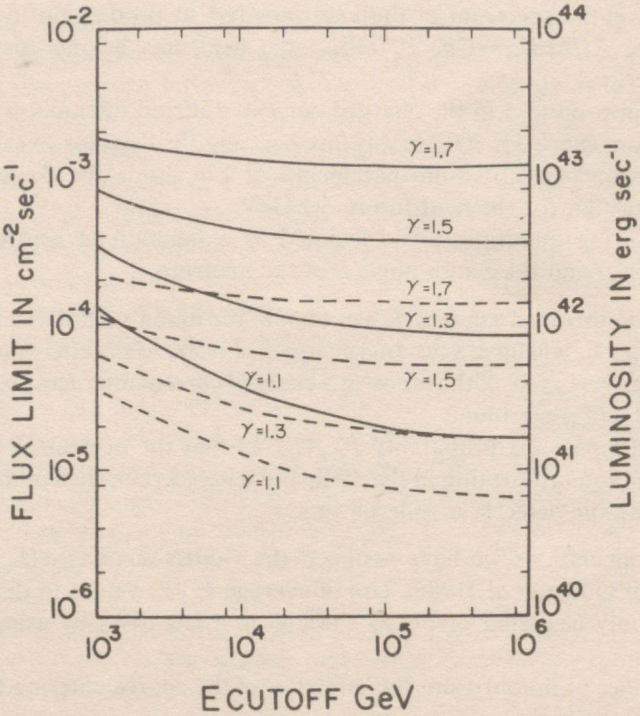


Figure 4. The 90 per cent confidence limits on the neutrino flux (solid lines and left vertical scale) and neutrino luminosity (dashed lines and right vertical scale) of SN1987A corresponding to the result of zero signal in KGF nucleon decay experiments. The values of γ correspond to the assumed differential spectrum $F(E)\,dE = CE^{-(\gamma+1)}\,dE$ and the horizontal scale to the maximum energy E_{cutoff} of the neutrinos from the source.

Our neutrino energy threshold of 1 GeV is low compared to that (1.7 GeV) of Oyama *et al.* (1987). The present result corresponds to the period upto 1989 March beginning from the supernova burst whereas the result of Oyama *et al.* covers a 6-month period from the burst. Moreover, the intervals of observation in each day do not exactly match due to the location of detectors and different zenith angular cuts for event selection. Thus these two experiments correspond to different intervals and duration in real time. However, our results agree within a factor of 2. These results give sufficiently stringent limits on the neutrino luminosities to rule out some of the models (Gaisser & Stanev 1987) of acceleration mechanism in supernovae which predict neutrino luminosities $>10^{43}$ erg s^{-1}.

Acknowledgements

We thank Messrs B. Satyanarayana, S. D. Kalmani, P. S. Murthy, R. Nagaraj and L. V. Reddy for able assistance in maintenance and data collecting. We are thankful to the Ministry of Education for partial financial support. The co-operation of the officers and other staff of the Bharat Gold Mines Ltd of KGF at all stages of the experiment is gratefully acknowledged.

References

Aglietta, M. A., Badino, G., Bologna, G., Castagnoli, C., Castallina, A., Dadykin, V. L., Fulgione, W., Galeotti, P., Kalchukov, F. F., Kortchaguin, V. B., Kortchaguin, P. V., Malguin, A. S., Ryassny, V. G., Ryazhkaya, O. G., Saavedra, O., Talochkin, V. P., Trinchero, G., Vernetto, S., Zatsepin, G. T., Yakushev, V. F. 1987, *Euro. Phys. Lett.*, **3**, 1315, 1321.

Alexeyev, E. N., Alexeyeva, L. N., Krivoscheina, I. V., Volchenko, V. I. 1987, Proc XXII Rcontre De Moriond, **1**, 739.

Bionta, R. M., Blewitt, G., Bratton, C. B., Casper, D., Ciocio, A., Claus, R., Cortez, B., Crouch, M., Dye, S. T., Errede, S., Foster, G. W., Gajewski, W., Ganezer, K. S., Goldhaber, M., Haines, T. J., Jones, T. W., Kielczewska, D., Kropp, W. R., Learned, J. G., Losecco, J. M., Mathews, J., Miller, R., Mudan, M. S., Park, H. S., Price, L. R., Reines, F., Schultz, J., Seidel, S., Schumand, E., Sinclair, D., Sobel, H. W., Stone, J. L., Sulak, L. R., Svaboda, R., Thornton, G., Van der Velde, J. C., Wuest, C. 1987, *Phys. Rev. Lett.*, **58**, 1494.

Blandfold, R. D., Ostricker, J. P. 1980, *Astrophys. J.*, **237**, 793.

Cavallo, G., Pacini, F. 1980, *Astr. Astrophys.*, **88**, 367.

Gaisser, T. K., Stanev, T. 1987, *Phys. Rev. Lett.*, **58**, 1695.

Ginzburg, V. L., Ptuskin, V. S. 1984, *J. Astrophys. Astr.*, **5**, 99.

Gunn, J. E., Ostricker, J. P. 1969, *Phys. Rev. Lett.*, **22**, 728.

Hirata, K., Kajita, T., Koshiba, M., Nakahata, M., Oyama, Y., Sato, N., Suzuki, A., Takita, M., Totsuka, Y., Kifune, T., Suda, T., Takahashi, K., Tanimori, T., Miyano, K., Yamada, M., Beier, E. W., Fieldscher, L. R., Kim, S. B., Mann, A. K., Newcomer, F. M., Van Berg, R., Zhang, W., Cortez, B. G. 1987, *Phys. Rev. Lett.*, **58**, 1419.

Krishnaswamy, M. R., Menon, M. G. K., Mondal, N. K., Narasimham, V. S., Sreekantan, B. V., Hayashi, Y., Ito, N., Kawakami, S., Miyake, S. 1982, *Phys. Lett.*, **115B**, 349.

Krishnaswamy, M. R., Menon, M. G. K., Mondal, N. K., Narasimham, V. S., Sreekantan, B. V., Hayashi, Y., Ito, N., Kawakami, S., Miyake, S. 1986, Il *Nuovo Cim.*, **9C**, 167.

Oyama, Y., Hirata, K., Kajita, T., Koshiba, M., Nakahata, N., Sato, N., Suzuki, A., Takita, M., Totsuka, Y., Kifune, T., Suda, T., Nakamura, K., Takahashi, K., Tanimori, T., Miyano, K., Yamada, M., Beier, E. W., Fieldscher, L. R., Kim, S. B., Mann, A. K., Newcomer, F. M., Van Berg, R., Zhang, W., Cortez, B. G. 1987, *Phys. Rev. Lett.*, **59**, 2604.

Quigg, C., Reno, M. H., Walker, T. P. 1986, *Phys. Rev. Lett.*, **57**, 774.