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

S. C. Tonwar,[a] N. V. Gopalakrishnan, S. K. Gupta, M. R. Rajeev, B. V. Sreekantan, and R. Srivatsan
Tata Institute of Fundamental Research, Homi Bhabha Marg, Colaba, Bombay 400 005, India
(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 $(6.4\pm1.6)\times10^{-12}$ cm^{-2}s^{-1} at energies $>2.5\times10^{14}$ 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 $>4\times10^{15}$ 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 ($-15.6°\pm2.0°$). 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 $>2.5\times10^{14}$ 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

 © 1991 The American Physical Society

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 $\geq 4.97\sigma$.

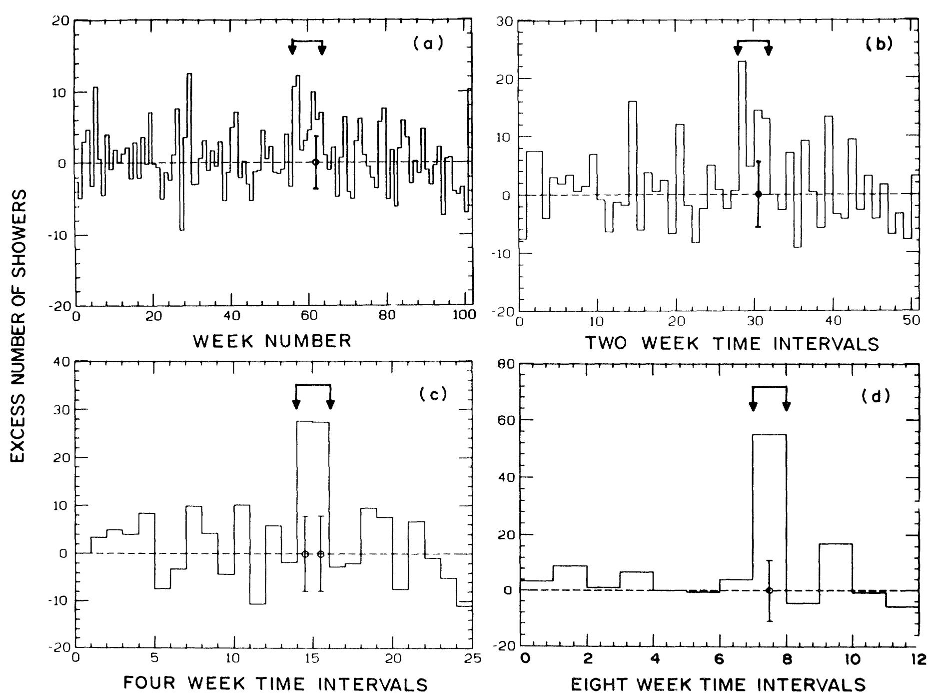

FIG. 1. Variation in the excess number of showers observed in the source bin relative to the average number observed in the background region as a function of time: (a) one week, (b) two weeks, (c) four weeks, and (d) eight weeks. The arrows indicate the period 4 March–2 May 1986.

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 $991/10^6 = 9.9 \times 10^{-4}$.

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 $9.9 \times 10^{-4}/1.8 \times 10^{-6} = 550$, 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 $> 2.5 \times 10^{14}$ eV has been estimated to be $(6.4 \pm 1.6) \times 10^{-12}$ $\mathrm{cm^{-2} s^{-1}}$ during this eight-week period. The measured value of the flux corresponds to a gamma-ray luminosity of 2×10^{35} $\mathrm{ergs\,s^{-1}}$ for Scorpius X-1 at energies $> 2.5 \times 10^{14}$ 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 $\mathrm{d^{-1}}$, compared to 0.262 ± 0.007 $\mathrm{d^{-1}}$ 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

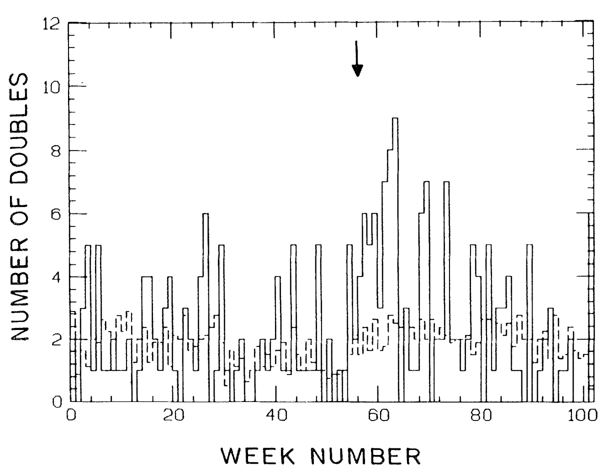

FIG. 2. Variation in the number of "doubles" observed per week from the direction of Scorpius X-1 (solid lines) and from the background region (dashed line), as a function of time. The arrow indicates the week starting on 4 March 1986.

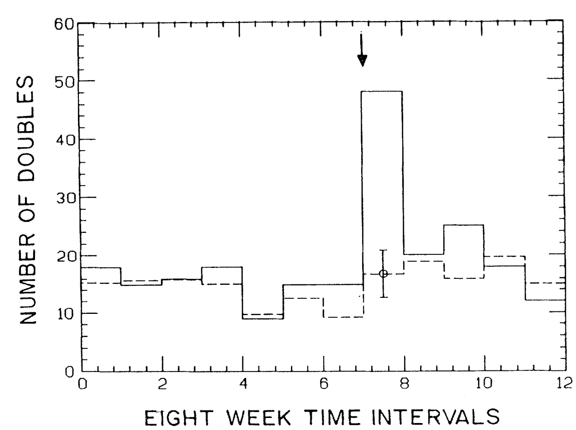

FIG. 3. Variation in the number of "doubles" observed during eight-week time intervals from the direction of Scorpius X-1 (solid line) and from the background region (dashed line), as a function of time. The arrow indicates the week starting on 4 March 1986.

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 $2.121 \pm 0.054\ d^{-1}$ for the source bin, simulations predict the double rate to be 0.281 d^{-1}, which is slightly smaller than the observed rate of $0.330 \pm 0.021\ d^{-1}$. 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 $3.18 \pm 0.24\ d^{-1}$ in the source bin, during the eight-week time interval 4 March–2 May 1986 simulations predict a double rate of 0.609 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 $(6.4 \pm 1.6) \times 10^{-12}\ cm^{-2} s^{-1}$ 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.

[a]Author to whom correspondence should be addressed. FAX: 91-22-215-2110. Electronic address: tonwar @tifrvax.bitnet.

[1] D. J. Fegan, in *Proceedings of the Twenty-First International Cosmic Ray Conference, Adelaide, Australia, 1989* (Graphic Services, Northfield, South Australia, 1990), Vol. 11, p. 23.

[2] S. C. Tonwar, TIFR Report No. OOTY-91/01, 1991 (to be published).

[3] J. Middleditch and W. C. Priedhorsky, Astrophys. J. Lett. **306**, 230 (1986).

[4] R. J. Protheroe and R. W. Clay, Nature (London) **315**, 205 (1985).

[5] T. Matano *et al.*, ICR Report No. 164-88-10, 1988 (unpublished).

[6] K. T. S. Brazier *et al.*, in *Proceedings of the Twenty-First International Cosmic Ray Conference* (Ref. [1]), Vol. 2, p. 296.

[7] B. V. Sreekantan, S. C. Tonwar, and P. R. Viswanath, Phys. Rev. D **28**, 105 (1983).

[8] A. R. Apte *et al.*, in *Proceedings of the Nineteenth International Cosmic Ray Conference, La Jolla, California,* NASA Conf. Pub. 2376 (U.S. GPO, Washington, DC, 1985), Vol. 3, p. 469.

[9] S. C. Tonwar *et al.*, in *Proceedings of the Nineteenth International Cosmic Ray Conference* (Ref. [8]), Vol. 1, p. 242.

[10] S. C. Tonwar *et al.*, Astrophys. J. Lett. **330**, L107 (1988).

[11] S. K. Gupta and S. C. Tonwar, J. Phys. G **17**, 1271 (1991).

[12] B. L. Dingus *et al.*, Phys. Rev. Lett. **61**, 1906 (1988).

[13] S. K. Gupta *et al.*, Astrophys. J. Lett. **354**, L13 (1990).

[14] S. K. Gupta *et al.*, Astron. Astrophys. **241**, L21 (1991).

[15] A. P. Cowley and D. Crampton, Astrophys. J. Lett. **201**, L65 (1975).