LETTERS

# Occultation of X-rays from Scorpius X-1 by small trans-neptunian objects

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**Since the discovery[1] of the trans-neptunian objects (TNOs) in 1992, nearly one thousand new members have been added to our Solar System[2,3], several of which are as big as—or even larger than—Pluto[4,5]. The properties of the population of TNOs, such as the size distribution and the total number, are valuable information for understanding the formation of the Solar System, but direct observation is only possible for larger objects with diameters above several tens of kilometres. Smaller objects, which are expected to be more abundant, might be found when they occult background stars[6–10], but hitherto there have been no definite detections. Here we report the discovery of such occultation events at millisecond timescales in the X-ray light curve of Scorpius X-1. The estimated sizes of these occulting TNOs are ≤100 m. Their abundance is in line with an extrapolation of the distribution[2] of sizes of larger TNOs.**

Because of the photon-counting nature of X-ray observations, X-ray occultation may stand a good chance of revealing the existence of small TNOs as long as the background X-ray source is bright enough to allow statistically meaningful determination at short timescales. Scorpius X-1 is the brightest and first-discovered X-ray source outside our Solar System[11]. It has been extensively studied and observed, particularly by the Rossi X-ray Timing Explorer (RXTE). In addition, Sco X-1 is only about 6° to the north of the ecliptic, making it the best target for a TNO occultation search. RXTE is a NASA mission launched at the end of 1995, providing the largest effective area of all X-ray satellites[12].

The Proportional Counter Array (PCA) instrument (2–60 keV) onboard RXTE registers a raw count rate of about $10^5$ counts per second from Sco X-1. Although PCA, with a one-degree field of view, has no imaging capability, the extremely high count rate from the point source Sco X-1 makes the sky and instrumental background both negligible. This high count rate also enables us to perform an examination on its light curve at timescales as short as one millisecond to search for possible occultation.

To search for occultation events, we examine all the time bins in the available RXTE/PCA archival data of Sco X-1 and compute their deviation distribution (Fig. 1). The deviation distribution of all the time bins in the light curve should be poissonian, modified by the dead-time and coincidence-event effects if all the fluctuations are random and there is no occultation event. The PCA data we used span over seven years from 1996 to 2002 and the total exposure time is about 322 ks. A log of all these data are listed in Supplementary Table 1.

In our search, we found obvious excess at the negative-deviation end in the deviation distribution. The excess becomes less significant for cases of larger bin sizes. Two of these distributions are plotted in Fig. 1. To check whether these negative-deviation excesses are instrumental, we performed the same search with PCA data for the Crab nebula, which is an extended X-ray source and is thus most suitable for checking whether those excesses are instrumental rather than due to occultations. Although the PCA count rate of the Crab nebula is about one-eighth of that of Sco X-1, a similar excess should still be detectable with enough data if it is instrumental in origin. From our search on 380-ks PCA data of the Crab nebula, no such excess was found. We also searched the PCA data of a candidate

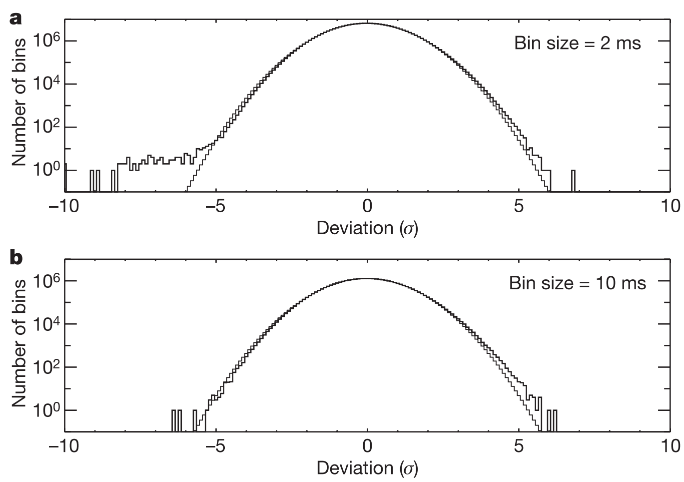


**Figure 1 | Deviation distributions of the Sco X-1 RXTE/PCA light curve.** The 'deviation' is defined for each time bin in the data as the difference between the photon number counts of that time bin and the mean counts per bin in a time window encompassing and running with the time bin in question. The 'deviation' is further expressed in units of the standard deviation of the photon counts per bin in the associated running window. In practice, the size of the running window should be large enough to have enough bins for the determination of the running mean and the standard deviation. However, it should not be too large, or the intrinsic flux level change of Sco X-1 will be involved. An adequate window size can be determined from comparing simulated distributions with computed (theoretically expected) ones. Searches for large deviation have been performed with all the available RXTE archival data, using different time-bin sizes from 1 to 10 ms with a window size of 8 s and time-bin sizes from 11 to 20 ms with a window size of 16 s. Here we show the deviation distributions for bin sizes of 2 ms (**a**) and 10 ms (**b**). Thick histograms are from the 322-ks RXTE/PCA data of Sco X-1 and thin histograms are gaussian distributions, plotted for comparison. To show the relatively small number of dip events, the ordinate is plotted in logarithmic scales. The excess at the negative deviation end in **a** is obvious. It becomes insignificant when the bin size increases to 10 ms. The small excess at the positive deviation part in both panels and the tiny deficiency between about $-3\sigma$ and $-5\sigma$ are due to the Poisson nature of the observed photons.

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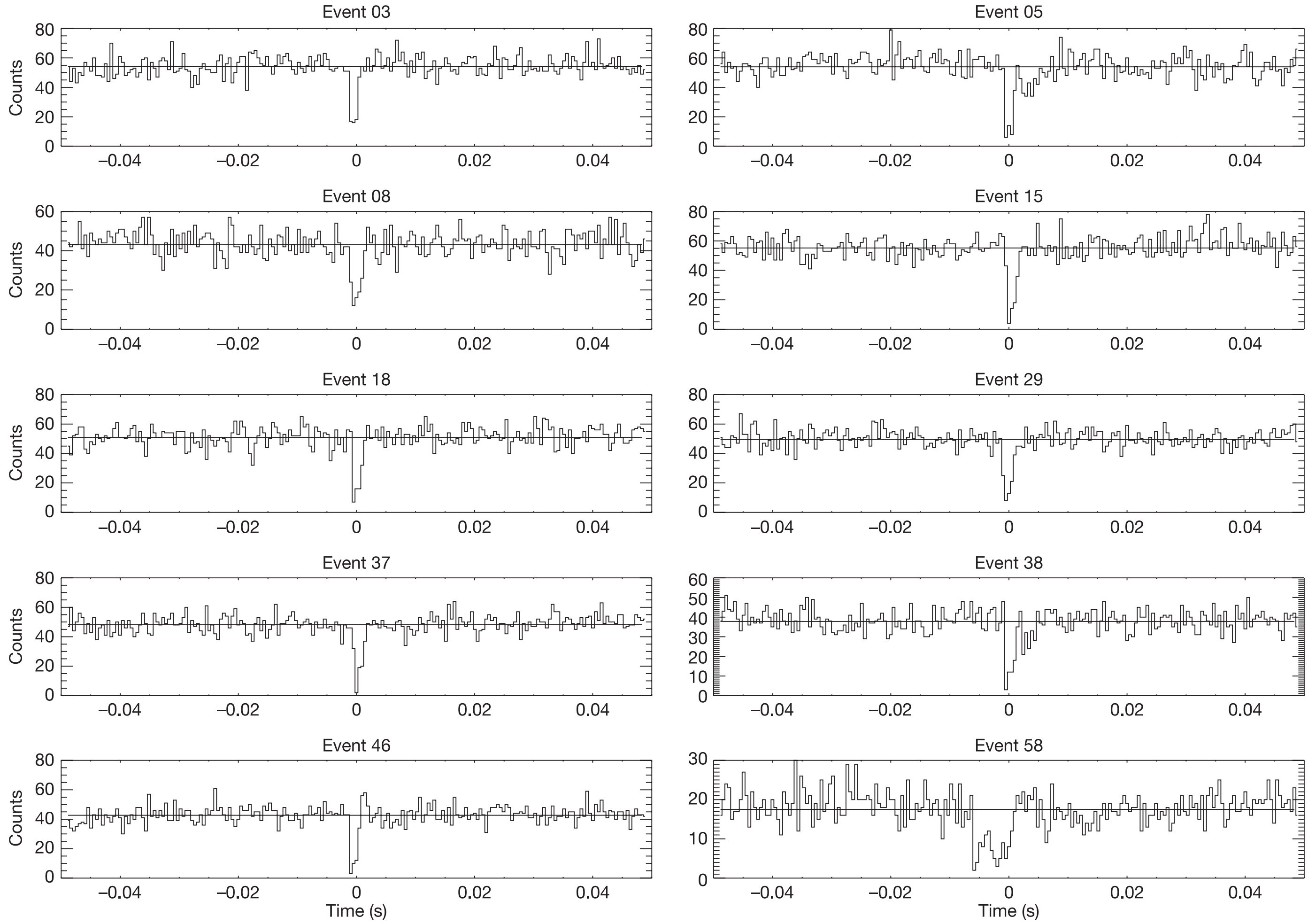


**Figure 2 | RXTE/PCA light curves of some example dip events.** 'Dip events' are identified as those time bins with a large negative deviation whose random probability is lower than $10^{-3}$. Assuming a gaussian probability distribution for simplicity, it corresponds to a negative deviation of about $6.8\sigma$ in the deviation distribution, depending on the total number of all time bins in that search, which, for example, is about $1.6 \times 10^8$ for the search with 2-ms time bins in the 322-ks data. Dip events may be repeatedly identified in searches with different bin sizes. In total, 58 dip events are found in the 322-ks data. We show the light curves of ten of the most significant events. Horizontal lines are the average counts in each panel. The histograms are plotted with a bin size of 0.5-ms. Events are numbered in sequence according to their occurrence time. Different count rates for different observations are due to the intrinsic flux variation of Sco X-1 and the number of PCUs turned on in that observation. Among the 58 events, more than a quarter show an asymmetric occultation light curve with fast drop in photon counts followed by slower recovery, like events 18 and 46 shown here. Only three are asymmetric in the opposite sense. Four events possibly show a complicated light curve like events 5 and 38 shown here. The others are roughly symmetric. All the light curves and more information on the 58 events can be found in Supplementary Fig. 1 and Supplementary Table 2.

accreting black hole, 4U 1543-47, which had an outburst in 1996 with a flux level about two to three times that of the Crab nebula for 4 ks. No negative-deviation excess was found for 4U 1543-47 either. Furthermore, as shown in Fig. 2, the count number drops in these time bins by a very large factor, indicating that these counts are not caused by malfunction of any single one of the five independent, almost-identical Proportional Counter Units (PCUs) of the PCA, although the recorded data mode does not contain individual PCU information. We therefore consider the excess very unlikely to be of instrumental origins.

In the 322-ks RXTE/PCA data of Sco X-1, 58 dip events with random probability lower than $10^{-3}$ were found. Some dip events are very significant, with deviation at a $10\sigma$ level. For example, event 18 in Fig. 2, when binned with a 2-ms bin size, has a deviation of $-10.7\sigma$. It corresponds to a random probability lower than $10^{-18}$ with the total number of time bins ($\sim 1.6 \times 10^8$) taken into account. The light curves of some of the most significant dip events are shown in Fig. 2. All 58 light curves can be found in Supplementary Fig. 1.

Sco X-1 is very bright. Almost all of the recorded multiple-anode events (events triggering more than two anodes in one PCU) are actually caused by two or more photons from Sco X-1 arriving simultaneously (within a coincidence window, typically of 5 µs; ref. 13). These multiple-anode events are usually rejected. Extremely bright flares might therefore be recorded as dips. However, the dips we found are not caused by flares, because the number of recorded two-anode events, which trigger both the L1 and R1 anodes in one PCU, drops at the same time for all 58 dip events, instead of increasing dramatically.

Most events have a duration of 2–3 ms and the longest one is 7 ms. The occurrence time of these 58 events seems random, based on the currently available data. The epochs and duration of all the 58 events are listed in Supplementary Table 2. We have also examined possible colour changes for the 33 events whose spectral information is available in a two-channel manner. We compared the ratio of counts in the two spectral channels with 200-ms bins, averaged over 4 s before and after the event. No significant colour change was found in any of these events.

It is difficult to attribute these dips to the intrinsic variability of Sco X-1. The luminosity variation of Sco X-1 at timescales from milliseconds to hours has been known for a long time[14–16]. These

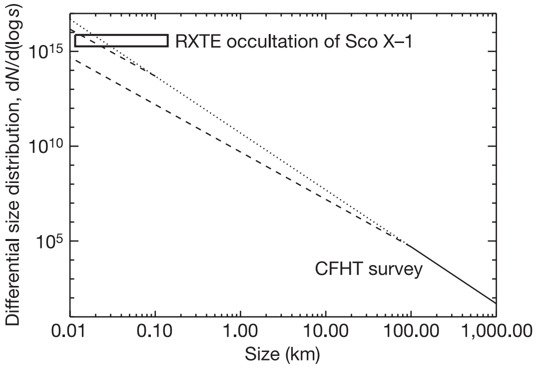


**Figure 3** | **The differential size distribution of TNOs.** **The total number of TNOs per decade of size—d*N*/d(log*s*)—inferred from the RXTE occultation of Sco X-1 is plotted as the bold rectangle at the upper left. Because of various assumptions made in this estimate (see Supplementary Discussion), an uncertainty level of a factor of two is adopted in this plot. The solid line ($dN/ds \propto s^{-q}$, where $q = 4.0$) near the lower right is the best fit of the Canada-France-Hawaii Telescope (CFHT) survey[2]. Its extrapolation towards smaller size is plotted as a dotted line. Two dashed lines corresponding to $q = 3.5$, as suggested by collisional erosion models[23,24], are plotted with turnover size at 0.1 and 100 km for comparison. Direct imaging of TNOs down to about 20 km in size can be achieved by the Hubble Space Telescope[25]. The Taiwanese-American Occultation Survey[9] (TAOS) is expected to detect occultation events caused by TNOs of kilometre size. Our discovery of the X-ray occultation demonstrates a new method of studying even smaller TNOs.**

variations happen with a small amplitude at all times in different activity states of the source, unlike the dip events we report here, which are sparse, abrupt, and always accompany a significant drop in flux. Millisecond X-ray flares have been observed in Cyg X-1 (ref. 17), and are very likely to be a manifestation of the lognormal nature of its X-ray flux[18]. The millisecond dips we report here are, however, dips, not flares, and the flux fluctuation of Sco X-1 is poissonian rather than lognormal.

There is strong evidence indicating that Sco X-1 contains a neutron star accreting from a companion of 0.4 solar masses[19] and the observed X-ray comes from the neutron-star surface and the inner part of the accretion disk, whose variability is related to the change of the accretion rate[20,21]. A sudden quench of plasma corona near the inner accretion disk of Sco X-1 might produce such dips but this would require an unusual cooling scheme. Objects such as neutron stars or stellar-mass black holes would need to have a transverse speed of several thousand kilometres per second to block Sco X-1 for a short duration of several milliseconds, and are thus also unlikely to cause the dips we observed.

We thus conclude that occultation by objects in the Solar System is the most plausible explanation to these dip events. The dimension of the X-ray-emitting region of Sco X-1 is controversial. The estimation ranges from 100 km to about 50,000 km, depending on different underlying models[20,21]. With a distance of 2.8 kpc (ref. 22), Sco X-1 occupies, at the most, a size of only 3 m at 40 AU (astronomical units) and more probably occupies only a few centimetres. It is even smaller at the distance of the main-belt asteroids. Taking Sco X-1 as a point source, the estimated occultation rate by the main-belt asteroids is extremely low (less than $10^{-9}\,s^{-1}$; details in the Supplementary Discussion). On the other hand, numerous larger TNOs have been discovered. An estimated total number of TNOs larger than 100 km within 30–50 AU is about $4 \times 10^4$ (ref. 2). Their differential size distribution follows the power law $dN/ds \propto s^{-q}$, where $s$ is the linear size of the TNO and $q$ is $4.0 \pm 0.5$ (refs 2, 3). Extrapolating this power-law distribution down to 20 m, which is roughly the smallest corresponding size of these dip events (see below), we obtain an occultation rate of about $4 \times 10^{-5}\,s^{-1}$ for a background point source. In the 322-ks exposure, about 12 occultation events can be expected. Our detection of 58 events is clearly more than that number but not by an order of magnitude.

The Fresnel scale, $R_F = (\lambda d/2\pi)^{1/2}$, for a distance of $d = 40$ AU and an X-ray photon of $\lambda = 0.6$ nm (2 keV), is about 20 m, which is a significant fraction of the TNO size that we are considering. It is possible to resolve the degeneracy of TNO size and distance with the X-ray diffraction pattern in the occultation light curves, which are related to the size, shape and distance of the TNO as well as that of the Sco X-1 emission region. However, the various shapes of the occultation light curves need to be corrected for the dead-time and photon-coincidence effects, if they are to be studied further, because Sco X-1 is very bright for PCA[13].

At present, we assume all the occulting TNOs are at a distance of 43 AU to estimate their size distribution. To convert event duration into TNO size, the relative projected speed on the sky of the RXTE with respect to the TNO in question at the corresponding epoch is needed. All the relative speeds and inferred TNO sizes of the 58 events are listed in Supplementary Table 2. Most of the events are due to TNOs about 50 m in size. As shown in Fig. 3, the inferred differential size distribution of TNOs of this size (Supplementary Discussion) is somewhat higher than the extrapolation from the best-fit distribution of TNOs larger than 100 km within 30–50 AU. We note that the discrepancy may still be within the uncertainty of that extrapolation, but numerical simulations of coagulation models for planet formation with collisional cascade predict a flatter distribution for smaller TNOs, with a turnover size between 0.1 and 100 km, depending on various properties of the early Solar System[23,24]. Our results seem to favour a smaller turnover size. However, it is possible that some of the 58 TNOs are at distances beyond 50 AU. It is also possible that another component of smaller TNOs may exist, particularly if the reported Hubble Space Telescope estimate[25] of the size distribution at about 30 km is reliable; this estimate is a factor of 25 lower than expected from the above extrapolation and is based on the Hubble Space Telescope detection of three TNOs within 0.02 square degrees of the sky.

More RXTE observations of Sco X-1 are needed to improve the statistics of our current results. Future X-ray observations of Sco X-1 and other sources with new instruments of higher sensitivity could build on this discovery to shed further light on the formation of our Solar System.

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**Supplementary Information** is linked to the online version of the paper at www.nature.com/nature.

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