

Millisecond dip events in the 2007 *RXTE*/PCA data of Sco X–1 and the trans-Neptunian object size distribution

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ABSTRACT

Millisecond dips in the *RXTE*/PCA archival data of Sco X–1 taken from 1996 to 2002 were reported recently. Those dips were found to be most likely caused by instrumental dead time but may also contain some true astronomical events, which were interpreted as the occultation of X-rays from Sco X–1 by trans-Neptunian objects (TNOs) of 100 m size. Here, we report the results of search for millisecond dip events with the new *RXTE*/PCA data of Sco X–1 taken in the year 2007. Adopting the same selection criteria as that in the previous study, we found only three dip events in 72-ks data, much fewer than the 107 events found in the 560-ks data taken from 1996 to 2002 reported earlier. The new data provide more detailed information of individual ‘very large events’ (VLEs), which is not available in the old archival data. Although the number of VLEs does not obviously increase during the occurrence of dip events, all the three dip events are coincident in time with VLEs that have no flags set for any of the propane or the six main xenon anodes. It is a strong indication of instrumental effects. No significant dips which might be real occultation by 60–100 m TNOs were observed. With only 72-ks data, however, the previously proposed possibility that about 10 percent of the dip events might not be instrumental still cannot be strictly excluded. Using the absence of those anomalous VLEs as the criterion for identifying non-instrumental dip events, we found, at a lower confidence level, four dip events of duration 8–10 ms in the 72-ks data. Upper limits to the size distribution of TNOs at the small size end are suggested.

Key words: occultations – Kuiper Belt – Solar system: formation – stars: neutron – X-rays: binaries.

1 INTRODUCTION

The outer Solar system bodies in the Edgeworth–Kuiper Belt and in the Oort Cloud are relics of the protostellar disc of the sun. These objects in the trans-Neptunian region witnessed the dynamical and collisional history of the early Solar system. Their properties, such as the total mass, size distribution, and orbital parameters, are therefore valuable knowledge for the understanding of the formation of our planetary system.

The first trans-Neptunian object (TNO) other than Pluto was discovered in 1992 (Jewitt & Luu 1993). More than 1000 TNOs have been found since then. These are all TNOs larger than 100 km. Smaller ones are too dim to detect. With much effort in data processing by integrating images over all possible TNO orbits, a *Hubble Space Telescope* survey reported the detections of three TNOs of size about 30 km (Bernstein et al. 2004). For even smaller ones, oc-

cultation of background stars as a way to study their properties was proposed 30 yr ago (Bailey 1976; Brown & Webster 1997; Roques & Moncuquet 2000; Cooray & Farmer 2003). Searches for such occultation events in optical bands have been conducted by some groups but without any definite detection so far. Some possible detections of TNOs of size about 300 m with 20-Hz photometry using the Bernard Lyot 2-m telescope of the Pic du Midi Observatory and the 4.2-m William Herschel Telescope at La Palma were reported (Roques et al. 2003, 2006).

At a shorter wavelength, millisecond dip events in the *RXTE*/PCA light curve of Sco X–1 were discovered (Chang et al. 2006), which were attributed to occultation caused by small TNOs of 100 m size. Later, signatures of possible instrumental effects related to high-energy cosmic rays for many of these dip events were found (Jones et al. 2006) and their nature became uncertain. A further analysis of 107 dip events in 560-ks *RXTE* archival data spanning over 7 yr from 1996 to 2002 indicated that the evidence for instrumental effects was not conclusive, mainly because of the coarse time-resolution of the relevant house-keeping data, and the possibility that about 10 per

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cent of these dip events are truly astronomical cannot be ruled out (Chang et al. 2007; Jones et al. 2008).

To distinguish instrumental and astronomical dip events in the *RXTE/PCA* light curve of *Sco X-1* and to explore the origin of the previously unknown instrumental effect, new *RXTE* observations of *Sco X-1* with a data mode recording detailed information of individual *RXTE/PCA* very large events (VLEs) at a time-resolution of 125 μ s have been scheduled. These observations started from 2007 June with two or three observations per week and carried out until 2007 October. The observation will resume from 2008 February for one more year. Here, we report the results of the observations in 2007, which already yielded useful information. We found that the presence of ‘anomalous VLEs (AVLEs)’, explained in the next section can be used as an indicator for instrumental effects. In the 72-ks 2007 *RXTE/PCA* data, three significant dip events similar to those reported earlier were found and they are all instrumental. At a less significant level of 5σ , 21 dip events were found and 17 of them are instrumental. With the four possible non-instrumental dip events, which are not inconsistent with random fluctuation, upper limits to the TNO size distribution at 100–300 m are suggested. These results are helpful for the analysis of new *RXTE/PCA* data in the future and for the design and operation of other X-ray space missions which may be suitable for TNO occultation search, such as India’s *ASTROSAT* and the proposed *Extreme Physics Explorer* (Elvis 2006).

2 DIP EVENTS AND THE ANOMALOUS VLEs

The 2007 *RXTE* observation of *Sco X-1* started from June 13 and ended on October 2. To have a higher count rate, we used only those data taken with three or more Proportional Counter Units (PCUs). Technical details of *RXTE* instrumentation can be found in the *RXTE* web site and also in Jahoda et al. (2006). A brief description of issues most relevant to our analysis can be found in Chang et al. (2007). Most of the observations were conducted with four or five PCUs. The total amount of the 2007 *RXTE/PCA* data used in this study is about 72 ks. To search for millisecond dip events, we adopted exactly the same procedure employed in previous studies (Chang et al. 2006, 2007). We examined the light curves of *Sco X-1* binned in different bin sizes from 1 to 10 ms. The deviation in photon counts of each bin in the light curve was determined by comparing its count number with the average counts and the count variance in an 8-s running window.

In our previous studies, the significance level adopted for identifying a dip event was set at the random probability being 10^{-3} for the 320-ks data employed in the first study (Chang et al. 2006). That corresponds to a deviation of $6.5\text{--}6.8\sigma$, depending on the bin size used in the search. To compare with the previous dip event rate, we used the same deviation level as the selection threshold to identify dip events in the new data. In total, in the 72-ks data, three dip events were found. Their light curves are shown in Figs 1–3 and epochs in Table 1.

The new observation has data modes recording information more detailed than before. In these data modes, detected photons are grouped into two sets. Set 1 includes those hitting PCU0, PCU2 and PCU4. Photons detected by PCU1 and PCU3 are in Set 2. Light curves of the three dip events from these two sets and their combination are shown in Figs 1–3. Furthermore, a newly designed data mode records individual VLEs with their detector (PCUs) and anode information at a time-resolution of 125 μ s. A VLE is an event that deposits more than about 100 keV energy in any one of the six active xenon-layer anodes or the propane-layer anode in each PCU

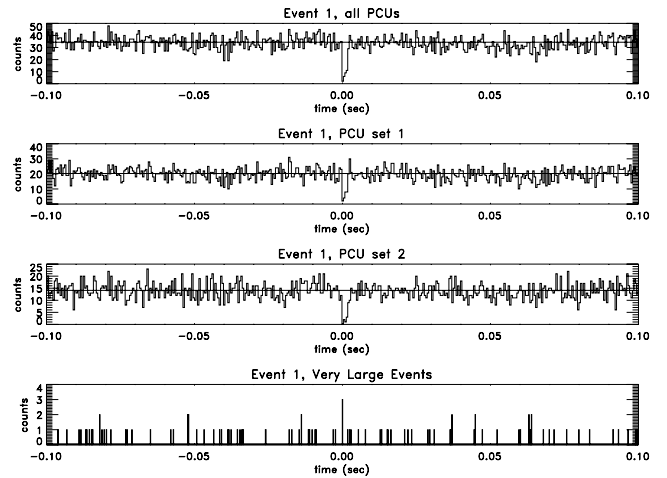


Figure 1. *RXTE/PCA* light curves of Event 1. Time zero refers to the epoch of Event 1, as listed in Table 1. The upper three panels are plotted with a 0.5-ms time-resolution. The light curve in the top panel is the sum of the two in the middle two panels. Plotted in the bottom panel is the count of ‘VLEs’ at a resolution of 125 μ s, which is also the designed resolution in the data. Some VLEs arrive at the same time (within 125 μ s). At the epoch of the dip events, the VLE count does not obviously increase; see Fig. 2 for a better example. However, all the three VLEs at the epoch of Event 1, and also those two for Event 2 and those three for Event 3, are anomalous in the sense that they do not have any flag set for any anode of the six main xenon layers or the propane layers. This kind of VLEs are called AVLEs in this paper and is used as the indication of a previously unknown instrumental effect.

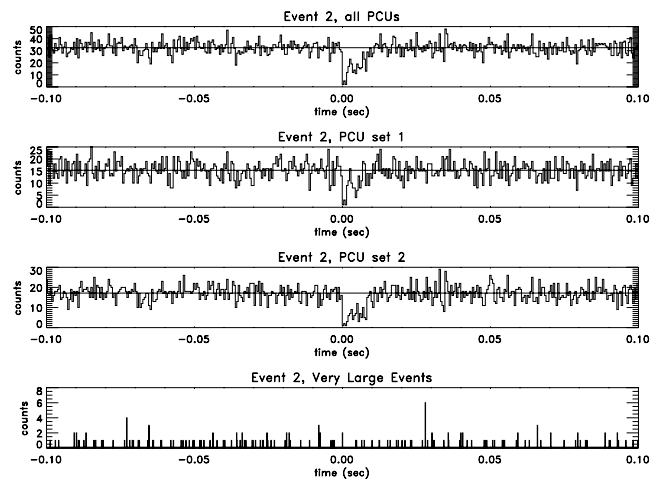


Figure 2. *RXTE/PCA* light curves of Event 2. See the caption of Fig. 1 for more explanations. We note that at the 28th ms after the Event 2 epoch, six VLEs arrive at the same time. There is nothing unusual in the light curves shown in the upper three panels at that epoch. The number of VLEs is apparently not related to the occurrence of dip events.

of the PCA onboard *RXTE*. The VLE counts around the epochs of these three dip events are also plotted in Figs 1–3.

The VLE counts do not particularly increase at the dip epochs. However, all the three dips are coincident in time with two or three VLEs that set no flags in the propane or the six main xenon anodes. We will call this kind of VLEs ‘AVLEs’ hereafter. It is not yet clear to us how AVLEs cause these dips and what AVLEs really are. Although further investigation on AVLEs requires detailed technical knowledge about *RXTE/PCA* and is beyond our capability, it is very

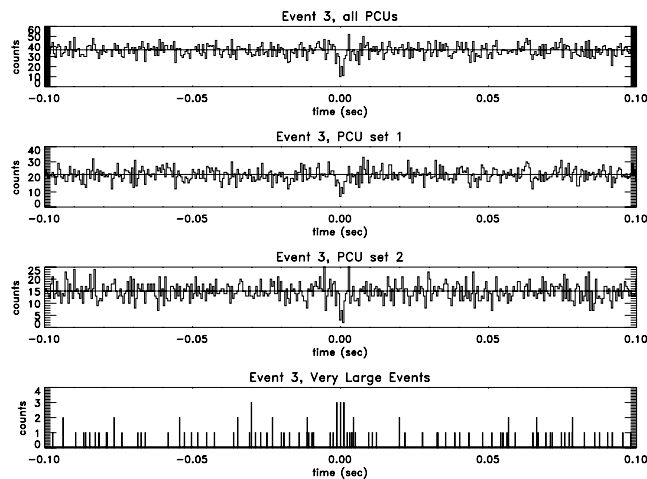


Figure 3. *RXTE/PCA* light curves of Event 3. See the caption of Fig. 1 for more explanations.

Table 1. Three most significant dip events and four non-instrumental dip events found in the 72-ks *RXTE/PCA* data of Sco X-1 taken in 2007. As explained in the main text, Events 1, 2 and 3 are all instrumental and Events A, B, C and D are not inconsistent with random fluctuations. The ‘Significance’ column shows the most significant deviation of the time-bins associated with the dip event. Noted in the parentheses are the corresponding bin sizes. For the exact definition of deviation and the dip search procedure, see Chang et al. (2006, 2007).

Event	Epoch (MJD)	Significance
1	54265.453357412	-8.4σ (2 ms)
2	54333.916753871	-11.5σ (8 ms)
3	54351.054678136	-6.8σ (2 ms)
A	54290.842075508	-5.2σ (9 ms)
B	54292.078448234	-5.0σ (10 ms)
C	54306.097132898	-5.0σ (8 ms)
D	54343.145430422	-5.0σ (9 ms)

likely that they are due to high-energy cosmic rays which induce particle showers in the instrument (Jones et al. 2006, 2008). This possibility is further supported by the excess of the so-called ‘remaining count’ recorded in the *RXTE/PCA* standard-1 data mode at dip epochs (Jones et al. 2006; Chang et al. 2007). Based on the occurrence of AVLEs at all the three dip epochs, we will use the presence of AVLEs as an indicator of instrumental effect to look for possible non-instrumental dips. We note, however, that the presence of AVLEs is a sufficient condition to indicate instrumental effects. Up to this point, one cannot be sure whether it is also a necessary one. At the epoch of Event 2, for example, the two AVLEs were detected by PCU2 and PCU4, both included in PCU set 1, but the light curve of PCU set 2 also shows the dip.

The number of dips found in the 2007 data seems much smaller than before. It is three in 72 ks, compared with 107 in 560 ks reported earlier (Chang et al. 2007). We note that, however, in the second half of year 1999, although the amount of the data used is 59 ks, no such dip events (significance higher than 6.5 – 6.8σ) were found. The dip event rate apparently varies. In the data prior to year 2007, there is no way to identify AVLEs. Although the three dips reported here are all instrumental, the possibility that 10 per cent of the earlier 107 events may be astronomical, that is, at a rate of about one per

50 ks, cannot be strictly excluded by the current non-detection in the 72-ks data.

3 POSSIBLE NON-INSTRUMENTAL DIPS AT A LOWER SIGNIFICANCE LEVEL

Equipped with the possibility of identifying non-instrumental dips by the absence of AVLEs, we proceeded to find dip events at a lower significance level. We tentatively set the deviation threshold at 5σ . With this threshold, we found in total 21 dips, in addition to the three more significant ones described in the last section. Among the 21 dips, 17 are associated with one to four AVLEs. In the data we used for this study, the average VLE rate is about 120 counts per second per PCU. The AVLEs happen at an average rate of about 1.8 counts per second per PCU, which is much smaller than the VLE rate. The association of 17 dips among the 21 with AVLEs further supports the validity of using AVLEs as the indication of instrumental effects. We therefore consider these 17 dip events being instrumental.

Light curves of the four dip events not associated with any AVLEs are shown in Fig. 4 and their epochs are listed in Table 1. These four dip events were picked out from searches with bin size of 8 (Event C), 9 (Events A and D), and 10 ms (Event B), respectively, at the 5σ level. In the 72-ks data, assuming a Gaussian distribution for the random fluctuation, we expect to see about two bins with a negative deviation more than 5σ in these searches. Although the Gaussian distribution in fact overestimates the number of expected bins at the negative deviation end because of the Poisson nature of the data, it is actually not much in the current case, as shown in Fig. 5. These four dip events are therefore not inconsistent with random fluctuations. We will use them to estimate upper limits to the TNO size distribution at the level set by assuming they are real occultation events.

4 UPPER LIMITS TO THE TNO SIZE DISTRIBUTION

The durations of these four events are roughly 8–10 ms. A rule-of-thumb estimate is that they correspond to a shadow of 240 to 300 m, assuming that they are occultation events. On the other hand, if they are caused by TNOs of that size (here we ignore all the

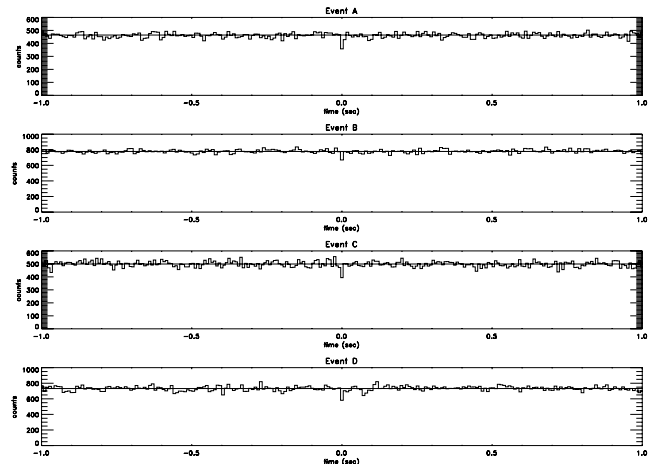


Figure 4. *RXTE/PCA* light curves of the four non-instrumental dip events. Time-resolution of these curves is 9, 10, 8 and 9 ms for Event A, B, C and D, respectively. Time zero refers to the epochs of these events, as listed in Table 1.

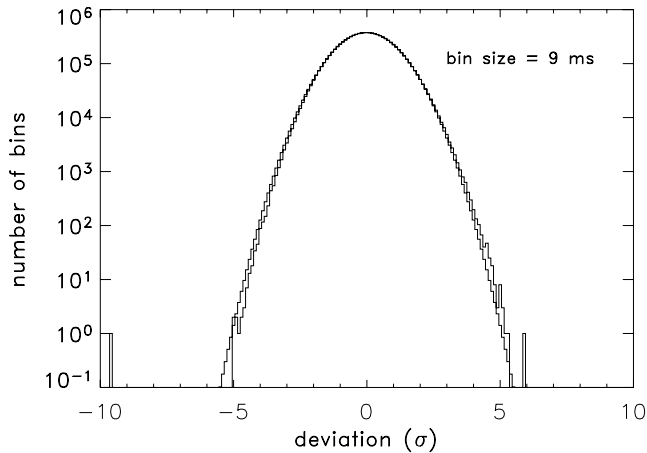


Figure 5. The deviation distribution of the Sco X-1 *RXTE*/PCA light curve with 9-ms bins. See Chang et al. (2006) for the exact definition of the deviation. The thick histogram is from the 72-ks *RXTE*/PCA data of Sco X-1 and the thin one is the Gaussian distribution, plotted for comparison. To show the relatively small number of events with large deviations, the ordinate is plotted in logarithmic scales. The bin at -9.6σ is associated with Event 2, whose light curve is shown in Fig. 2. Those bins at about -5σ are not inconsistent with random fluctuations.

complexity of diffraction patterns and the crossing location in the shadow), those TNOs should be at a distance much farther than that of most TNOs discovered to date, because their shadows are very shallow. Let us consider this with the notion of the ‘flux-drop fraction’ defined in Chang et al. (2007). The flux-drop fraction of these four events is about 0.2 or so. From fig. 13 in Chang et al. (2007), one can see that at 40 au a flux drop of 0.3 corresponds to the object size being about 30 m, that is, one Fresnel scale, which is $\sqrt{\lambda d/2}$, where λ is the wavelength and d is the distance. We use $\lambda = 0.3$ nm (4 keV) because most of the *RXTE*/PCA-detected photons from Sco X-1 are at this energy. We note that, for a given ratio of the object size to the square root of the distance, the diffraction patterns are the same, when expressed in units of the Fresnel scale (e.g. Roques, Moncuquet & Sicardy 1987). The flux-drop fraction is therefore also the same for these patterns. Since the flux drop of the four possible non-instrumental events is about 0.2, instead of 0.3, the distances to the objects causing these events will be beyond 4000 au, but not by orders of magnitudes, if their sizes are all about 300 m. On the other hand, their sizes are likely to be smaller than 300 m. At first, assuming a shadow-crossing speed of 30 km s^{-1} , their duration implies sizes of 240–300 m. Secondly, the shadow-crossing speed is probably smaller than 30 km s^{-1} , so the size could be even smaller. To produce a certain level of flux drop, a smaller size implies a smaller distance. To simplify the discussion, we adopt 4000 au as a representative distance to these objects. This distance is in the inner Oort Cloud region.

The above estimate is of course a rough one, which we consider adequate at the current stage. A more detailed approach may be devised by considering the event duration and the flux-drop fraction as functions of the TNO size and distance, with the *RXTE* velocity in the Solar system at the epoch of each particular event, assumed orbital parameters of the TNO, assumed TNO shape and shadow-crossing location (the impact parameter), and the corresponding diffraction pattern. Such an approach will be reported in details in another forthcoming paper. Here, we contend ourselves with the above estimate. We propose to derive an upper limit to the total number of a certain population of TNOs located around 4000 au at

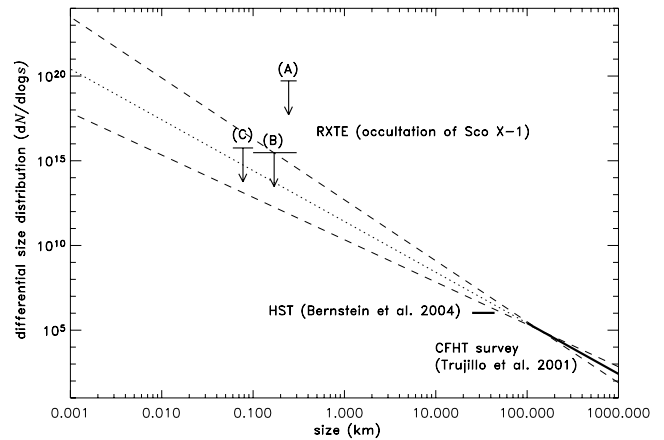


Figure 6. The differential size distribution of TNOs. The three upper limits to the total number of TNOs per decade of size ($\frac{dN}{d \log s}$) inferred from the *RXTE* observation of Sco X-1 are plotted as the horizontal bars with the downward arrows and labels (A), (B) and (C). The estimation of these three upper limits is described in Section 4. The upper limit (A) is not to compare with any others in this figure, since all the others are for the TNO population in 30–50 au, while the upper limit (A) refers to that at about 4000 au. The solid and dotted lines are the best fit from the CFHT survey (Trujillo et al. 2001) and its extrapolation towards smaller sizes. The dashed lines mark its 1σ uncertainty in the power index of the distribution. Direct imaging of TNOs down to size of about 30 km was reportedly achieved by the *Hubble Space Telescope* (Bernstein et al. 2004), whose estimated TNO size distribution at about 30 km is a factor of 25 below the extrapolation of the aforementioned CFHT survey. Optical occultation search may be able to detect occultation events caused by TNOs of kilometre size.

the level of assuming the four dip events being real occultation by objects of size 200–300 m. From equation (4) in Chang et al. (2007), which we quote below for convenience,

$$\left(\frac{dN}{d \log s} \right)_{s_1 < s < s_2} = \frac{d^2 \Omega_A}{v(s_2 - s_1)} \frac{N}{T} \ln 10, \quad (1)$$

and with $\Omega_A = 3.4$, $v = 30 \text{ km s}^{-1}$, and $T = 72 \text{ ks}$, we have in the size range from 200 to 300 m

$$\left(\frac{dN}{d \log s} \right) \approx 5.2 \times 10^{19}. \quad (2)$$

This upper limit is plotted in Fig. 6 with the label ‘(A)’. In equation (1) Ω_A is the sky area covered by the population of TNOs in question. It may not be equal to 3.4 as derived from the CFHT survey for TNOs larger than 100 km (Trujillo, Jewitt & Luu 2001; Chang et al. 2007), but the difference will not be orders of magnitudes. We in fact do not have the knowledge about that for objects in the inner Oort Cloud.

Since in the 72-ks data we did not find any dip events possibly caused by TNOs at about 43 au, we proceed to set an upper limit to the size distribution in the range of 100–300 m, which roughly corresponds to dip durations of 3–10 ms. A mimic 2σ upper limit can be set at the level of four events in 72-ks data. This is of course not in a rigorous statistical sense, but just to illustrate the order of magnitude in the size distribution. From equation (1), we have $\left(\frac{dN}{d \log s} \right) \approx 3.0 \times 10^{15}$. This upper limit is plotted in Fig. 6 with the label ‘(B)’. In the size range of 60–100 m, Chang et al. (2007) suggested possible detection of about 12 events. However, the three significant dips reported in Section 2 are all instrumental and no dips that might be real occultation by 60–100 m TNOs were observed. We therefore set the upper limit at the level of 12 events in 560 ks

for the size range of 60–100 m. This upper limit is plotted in Fig. 6 with the label ‘(C)’.

The upper limits proposed above are not quite constraining, and there are considerable uncertainties in the estimate. Nevertheless, they point out a way to acquire information for that size range, which is probably impossible to achieve with optical observations. In the visible light, the Fresnel scale at 40 au is about 1 km. It is difficult to detect occultation by objects much smaller than that size at 40 au or beyond. The detectability is further constrained by many other issues related to the background stars and the observing facility. A detailed study on the detectability of optical occultation search can be found in Nihei et al. (2007). It is similar for the case of X-ray occultation search. The Fresnel scale at 40 au for 4-keV photons is about 30 m. Any significant occultation dip events will have a duration longer than 1 ms, unless the occulting body is at a shorter distance. To detect dips in the light curves at millisecond time-scales, the photon count rate needs to be high enough. The *RXTE/PCA* count rate of Sco X–1 is about 10^5 counts per second, which makes detection of millisecond dips feasible. A more detailed analysis on the X-ray occultation detectability with *RXTE/PCA* observation of Sco X–1 will be reported in another forthcoming paper. We note here that at 4000 au objects much smaller than 300 m will not be detected by X-ray occultation.

Most model computations expect that the size distribution of TNOs in 30–50 au at the small size end falls below the extrapolation of the power law of objects larger than 100 km (e.g. Kenyon & Bromley 2004; Pan & Sari 2005; Charnoz & Morbidelli 2007). The suggested upper limits labelled with (B) and (C) in Fig. 6 are both above the power-law extrapolation and thus provide no discrimination power to the current theory. To push down the upper limits to the level close to the power-law extrapolation, about 60 times the current data volume is needed, that is, about 4.3 Ms, or 50 d of continuous observation. If a new instrument more sensitive than *RXTE/PCA* is available, other X-ray sources dimmer than Sco X–1 may also be used for such a search. Finally, if definitely true occultation events are found, it will have strong impact on our understanding of the early Solar system. Deployment of an array of X-ray satellites in a region of 300 m or so will help to further affirm the reality of any detected X-ray shadows and to yield more information about the occulting TNOs.

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