Millisecond Dips in Sco X-1 are Likely the Result of High-Energy Particle Events

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ABSTRACT

Chang et al. (2006) reported millisecond duration dips in the X-ray intensity of Sco X-1 and attributed them to occultations of the source by small trans-Neptunian objects (TNOs). We have found evidence that these dips are in fact not astronomical in origin, but rather the result of high-energy charged particle events in the RXTE PCA detectors.

1. Introduction

Chang et al. (2006) found statistically significant one to two millisecond duration dips in the count rate during X-ray observations of Sco X-1 carried out with the Proportional Counter Array (PCA) on the Rossi X-ray Timing Explorer (RXTE) and attributed them to occultations of the source by small objects orbiting the Sun beyond the orbit of Neptune, i.e., trans-Neptunian objects (TNOs). In all, Chang et al. (2006) found some 58 dips in approximately 322 ks of Sco X-1 observations. Given that the RXTE spacecraft moves through the diffraction-widened shadows of any TNOs at a velocity of \(\sim 30 \text{ km s}^{-1}\), dips of \(\sim 2 \text{ ms}\) duration should correspond to a TNO size of \(\sim 60 \text{ m}\). If the identification of these dips with occultations by TNOs is correct, the dips would provide extremely valuable information on the number and distribution of solar system objects of \(\sim 20\text{-}100 \text{ m}\) in size.

2. Average Properties of Dips in the Sco X-1 Count Rates

Subsequent to the report by Chang et al. (2006), we identified \(\gtrsim 200\) dips of the type they describe in some 500 ks of RXTE/PCA observations of Sco X-1. In an attempt to detect the small counting rate \textit{increases} that one might expect from diffraction sidelobes if these are indeed occultation events, we formed an average dip profile by superposing the PCA light curves that include the dips. This was done after fitting a Gaussian to each dip in order to estimate its centroid time, maximum depth, and width. We use the full width at half maximum (FWHM) of the fitted Gaussian as our estimate of dip width. Then, using the fitted centroid time and dip

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width, we shift and stretch each dip to a common centroid time and width before accomplishing the superposition. We expected to see sidelobes with intensity $\sim 5\%$ greater than the mean count rate determined substantially away from the superposed dips. We find no evidence for diffraction sidelobes in the superposed light curves, despite having statistics sufficient to reduce fluctuations to $\sim 1\% (1 \sigma)$ of the mean count rate.

Three additional problems with the occultation interpretation are manifest from the dip profiles. First, the summed dip profile is distinctly asymmetric in shape (as Chang et al. suggested for many of the individual dips). Second, the distribution of dip widths is narrower than what one would expect from occultations by bodies with a power-law size distribution of index $-4$, i.e., there are fewer than expected statistically significant dips with Gaussian FWHM widths greater than $\sim 2$ ms. Third, when diffraction effects are taken into consideration, the majority of dip widths are shorter than the minimum widths one would expect from occultations by bodies at distances of $\sim 40$ AU regardless of their size distribution.

3. Search for an Alternate Explanation

These findings prompted us to further explore alternative explanations for the dips. Only one hypothesis appeared to be worthwhile to pursue, viz., that the dips are caused by electronic dead time in response to some type of charged particle shower in the spacecraft (see Jahoda et al. 2006, and references therein, for technical information on the PCA). Coincidences within a $\sim 10$ $\mu$s window among two or more of the measurement chains in a Proportional Counter Unit (PCU) are used to identify charged particle events. However, the intensity of Sco X-1 is so high that there is a substantial rate of coincidences due to the detection of two X-ray photons within the $10$ $\mu$s window. For some observations, the rates of such so-called two-LLD events were telemetered with millisecond time resolution; the dips are apparent in these data as expected. In contrast, no information is available on the non-X-ray background during the Sco X-1 observations with millisecond time resolution. Counts of good events, very large events (VLEs), propane-layer events, and a catch-all category of other types of events that includes multiple LLD events are available at 1/8 s time resolution from Standard Mode 1; most other types of data are only available with 16-s time resolution.

The VLE flag for a PCU is set when the electronics detects an event in that PCU with energy greater than $\sim 100$ keV; this can happen in response to the ionization produced by a single charged particle or to that produced by multiple charged particles which penetrate the detector nearly simultaneously. Such a large event can produce ringing in the front-end of an electronic measurement chain. Therefore, in response to the occurrence of a VLE, the digital logic shuts down the electronic processing of events in that PCU for a fixed time period, chosen to be 50 $\mu$s for almost all of these Sco X-1 observations. In addition, each of the 6 main xenon layer measuring chains is disabled until its charge drops to an acceptable level. In order for the detector to be shut down for an extended period ($> 1$ ms), an extraordinary amount of charge must be deposited on
Fig. 1.— Counts per 1/8-s time bin of different types of PCA detector events superposed, i.e., averaged, around the times of 201 dips. The superposition was accomplished such that the bin at time $= 0$ s includes the identified dips. The counts include events from all (typically 3 to 5) of the operating PCUs. Top panel: good xenon counting rate data. The decrease in counting rate due to the dips is apparent. The small ($\sim 0.6\%$) drop in the counting rate is explained in the text. Middle panel: counting rate data of events that are not good events, propane-only events, or VLEs. This category includes multiple-LLD events (see text). A highly significant enhancement in the vicinity of the dips is evident. Bottom panel: VLE event rate data superposed around the dip times, also showing a statistically significant peak. Note that the peak in the VLE event rate is approximately one VLE event per detector per dip event (i.e., $\sim 4$ excess events per dip).
most of the 6 main measuring chains; it is unclear, at present, whether this can happen in response to a single charged particle.

The prime purpose of the propane layer is to distinguish events caused by soft ($\sim 1$ MeV) electrons from those caused by X-rays. However, Sco X-1 is such a strong source that during observations of Sco X-1 the bulk of the events seen only in the propane layer are due to X-rays from the source. If the source flux is diminished due to an intervening TNO, we would expect that the propane rate would decrease similarly to the xenon rate.

Figure 1 shows counts of three different types of events in 1/8-s time bins superposed around the times of 201 dips. In each panel, the centers of the short ($\sim 2$ ms) dips have been placed in the bin at $time = 0$. The top panel shows the rates of good events, i.e., those not identified as being due to charged particles, in the main xenon layers of all operating PCUs, and clearly shows the superposed dips; two-LLD events are not included in these rates. The counting rate drops by only $\sim 0.8\%$ because of the dilution of a $\sim 2$ ms dip within a 128 ms wide bin. By contrast, the middle panel shows the enhancement of the counting rate in Standard Mode 1 “other” events in the vicinity of the dips. The peak is highly significant ($\sim 38 \sigma$). The bottom panel corresponds to the VLE event rate superposed around the dip times. This peak is also statistically very significant ($\sim 8 \sigma$). The increase in the VLE rate is more or less consistent with the detection of $\sim 1$ VLE per PCU per dip.

The enhancements in the other event and VLE rates around the times of the dips indicate that there is an increase in the rate of detection of non-X-ray events. We speculate that these non-X-ray events interrupt normal event processing for 1-2 milliseconds in all or most of the PCUs roughly once per hour due to the collection of very large amounts of charge. Such an energetic event may be the consequence of a particle shower produced by the collision of a high-energy cosmic ray with a nucleus in the RXTE spacecraft. In any case, further clarification of the causes of the observed dips would be of interest.

4. Conclusions

While our results cast doubt on whether any true occultation events have been detected, one cannot yet conclude that no such events have been detected. We intend to conduct further investigations of the dip phenomenon and its possible causes, and we will work to obtain a new measurement of, or upper limit on, the rate of occurrence of occultations of Sco X-1.

\footnote{These were incorrectly identified as propane-only events in the first version of this paper.}
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