Search for High Energy Emission from AXPs

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Abstract The X-ray emission from Anomalous X-ray pulsars (AXP) is generally soft, and therefore their spectral and temporal properties have been characterized with soft X-ray instruments usually operating below 30 keV. However, recent detection of 1E 1841−045 with the INTEGRAL observatory and the subsequent analysis with the PCA, BeppoSAX, and HEXTE showed that higher energy emission, up to 100 keV, is present for this source. Over the course of the *RXTE* mission, there have been numerous observations of various AXPs, resulting in a rich archival dataset. Using these observations, we have searched for pulsed high energy emission from all known AXPs except 1E1048−59. Here, we report on our findings from this search, and compare the results from the expectations of different models that describe the high energy emission from AXPs.

Introduction

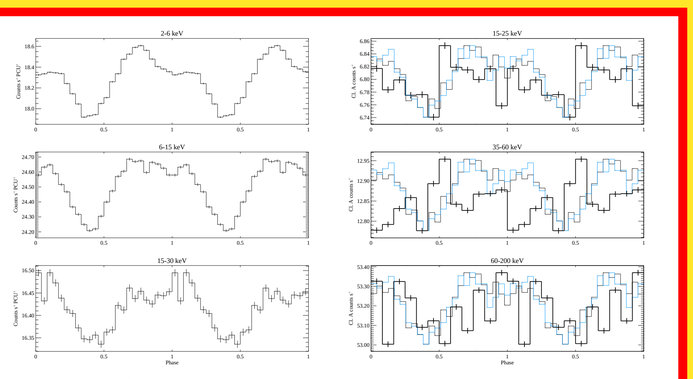
The AXPs are isolated neutron stars with periods clustered in the narrow range of 6–12 s. The X-ray luminosities, periods, and blackbody temperatures of AXPs are similar to those of soft gamma-ray repeaters (SGRs). Moreover, SGR like bursts have been detected from two AXPs strengthening the connection (see Woods 2004). There had been estimates of the strength of high energy emission from AXPs using the "magnetar" (outer gap model with magnetar fields, not to be confused with the model in the very recent preprint by Thompson & Belobedorov, astro-ph/0408538), and the "disk-star dynamo" models. These models predict flux levels below the detection limits of current instruments in the hard X-ray band, even for reasonably long observations (e.g. 15–200 keV band estimated integrated fluxes for 4U0142+61 are $\sim 5 \times 10^{27}$ and $\sim 6 \times 10^{31}$ ergs s^{-1} for the magnetar and the disk-star dynamo model respectively, Ertan & Cheng 2004). The detection of 1E 1841−045 with the IBIS instrument on *INTEGRAL* and the subsequent detection with HEXTE on *RXTE* (Kuiper, Hermsen & Mendez, 2004) was a surprising and important development in the study of these sources. Using the archival *RXTE* data, we started a project to systematically search for high energy emission (15–200 keV) from all AXPs with HEXTE, and the results are presented below.

Observations and Data Analysis

We generated bary-center corrected light curves with 0.0625 s time resolution from both the PCA and the HEXTE instruments on *RXTE* for 5 confirmed AXPs. A dead-time correction was also applied to the HEXTE light curves. Cluster A data were used for all AXPs, whereas Cluster B light curves were accumulated for 1E1841−045 for test purposes. Both the source and the background light curves were accumulated for HEXTE. For each source, the light curves were folded with timing solutions in the literature using 24 bins for each cycle for both PCA and HEXTE (see boxes for individual sources for the timing solutions used and the total observing times). Subsequent rebinning applied to the folded HEXTE light curves. Due to the strong timing noise of 1E1048−51, the process of finding appropriate timing solution valid for long times is still underway. We used 2–6 keV, 6–15 keV, and 15–30 keV bands for the PCA, and 15–25 keV, 35–60 keV, and 60-200 keV bands for HEXTE, avoiding the strong background feature in the HEXTE spectrum. To increase the statistical quality of the HEXTE data, very long stretches of observation times were accumulated (from 1996 to 2003), and often the folded light curves in one stretch of time were not exactly phase coherent. We offset our data sets using a template to preserve the pulse shapes. Similar methods were applied by Kuiper, Hermsen & Mendez (2004) for the analysis of 1E1841−045 using HEXTE.

1E1841−045

PCA Observing time: ∼254 ks
HEXTE Cluster A observing time: ∼130 ks
Date range and corresponding timing solution reference:
02/15/1999 – 01/27/2003, Gotthelf et al. (2002)



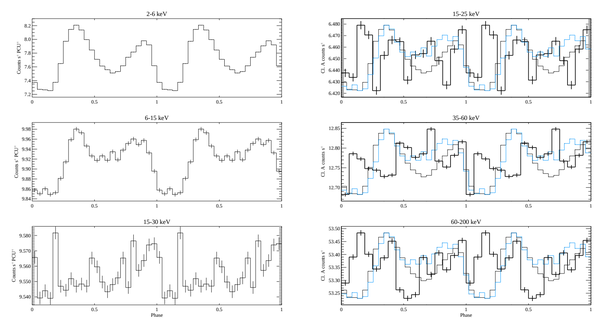
PCA folded light curves in 2–6 keV, 6–15 keV, and 15–30 keV bands. The pulse is apparent in all energy bands with similar shapes. The position of the minimum does not change with energy.

HEXTE folded light curves in 15–25 keV, 35–60 keV, and 60–200 keV bands are shown with thick solid histogram. The PCA folded light curves in 2–6 keV and 6–15 keV (renormalized to fit into the figure panel) are also shown for comparison.

This source has strong pulsed emission above 15 keV as seen in both the PCA 15–30 keV folded light curve and the HEXTE 15–25 keV folded light curve. The 60-200 keV in HEXTE also has a similar pulse shape, although the 35–60 keV HEXTE folded light curve does not follow the PCA pulse.

1E2259+58

PCA observing time ∼570 ks
HEXTE cluster A observing time ∼330 ss
Data ranges and corresponding timing solution references:
09/29/1996 – 12/13/1997, Baykal et al. (1998)
08/13/1998 – 05/04/2002, Kaspi, Chakrabarty & Steinberger (1999)
06/30/2004 – 02/15/2003, Woods et al. (2004)



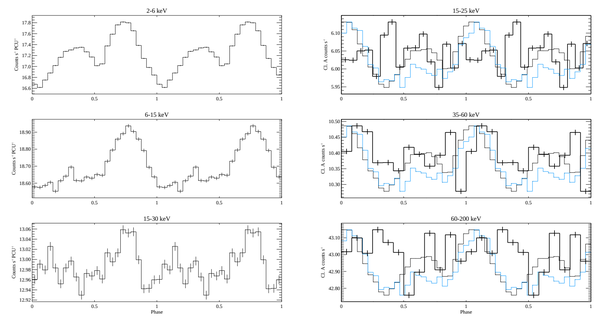
PCA folded light curves in 2–6 keV, 6–15 keV, and 15–30 keV bands. The 15-30 keV band only shows one of the peaks, and weaker in strength.

HEXTE folded light curves are shown with thick solid histograms. The PCA folded light curves in 2–6 keV and 6–15 keV bands are also shown for comparison.

This source does not show a HEXTE pulse in any band that is consistent with PCA pulse shapes. The 15-25 keV band in HEXTE does not show a pulse at all. Although 60-200 keV band appears to be pulsed, it is almost out of phase with the PCA pulse.

4U0142+61

PCA total observing time ∼142 ks
HEXTE cluster A observing time : ∼72 ks
Date range and corresponding timing solution reference:
03/25/1996 - 11/26/2002, Gavriil & Kaspi (2002)



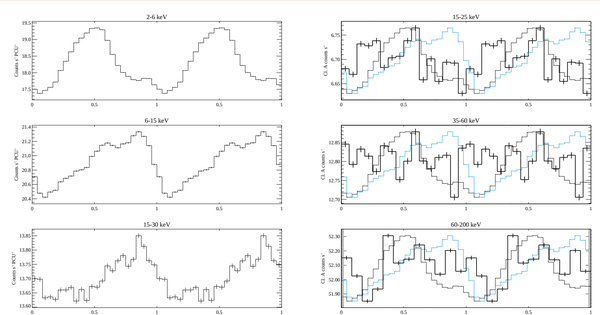
PCA folded light curves in 2–6 keV, 6–15 keV, and 15–30 keV bands. The 15-30 keV band only shows one of the peaks.

HEXTE folded light curves are shown with thick solid histograms. The PCA folded light curves in 2–6 keV and 6–15 keV bands are also shown for comparison.

This source does not show a HEXTE pulse in any band that is consistent with PCA pulse shapes.

1RXS J1708-4009

PCA total observing time : ∼194 ks
HEXTE cluster A total observing time: ∼130 ks
Date range and corresponding timing solution reference:
01/12/1998 – 02/06/2003, Kaspi & Gavriil (2003)



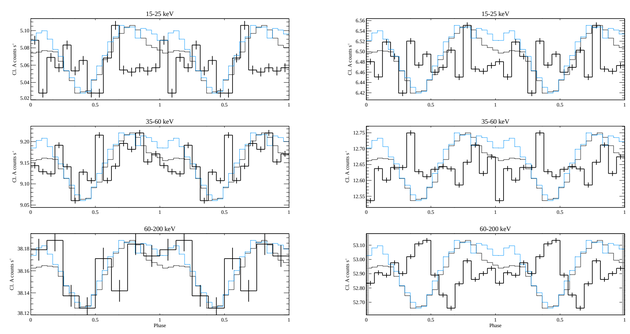
PCA folded light curves in 2–6 keV, 6–15 keV, and 15–30 keV bands. Notice the change in pulse shape from 2-6 keV to higher bands. The minima do not change.

HEXTE folded light curves are shown with thick solid histograms. The PCA folded light curves in 2–6 keV and 6–15 keV bands are also shown for comparison.

HEXTE 15-25 keV band folded light curve seems to show a pulse out of phase with the PCA pulse, there appears to be no pulse at 35–60 keV, and **a pulse like structure is present at 60–200 keV, but not exactly in phase with the PCA 15–30 keV pulse.**

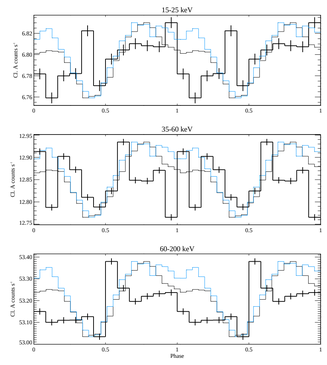
HEXTE DATA ANALYSIS ISSUES

Extreme caution is required when analyzing and interpreting results from the folded light curves of AXPs (or any weak source) obtained with HEXTE. Below, we show results of various tests we applied to validate detection of pulsed emission from our sources.



1E1841−45 folded light curves using HEXTE Cluster B.

1E1841−45 folded light curves using HEXTE Cluster A background.



1E1841−45 folded light curves using HEXTE Cluster A and a random period in 6-12 s band.

To confirm the detection of high energy pulsed emission from 1E 1841−45, we conducted three tests: **(1) pulse folding with Cluster B, (2) pulse folding with background, and (3) pulse folding with random periods in the 6-12 s band**.
One can see that the Cluster B folded light curve tracks the PCA light curves, increasing the level of confidence on the detection. An additional confirmation is the detection of source with IBIS on *INTEGRAL* (Kuiper, Hermsen & Mendez, 2004). Having said that, **the 60-200 keV band cluster A *background* folded light curve also shows a pulse as strong as the source pulse, but with a different phase.** For all sources, we observe pulse like structures in HEXTE background folded light curves with rms amplitudes comparable to that of source folded light curves. We also tried folding the source light curve of 1E 1841−45 with random periods in AXP period range, and obtained the pulse shown in the figure for our second try! The PCA folded light curves at the same random period did not show a pulse.

Discussion

We have calculated the rms amplitudes of the folded HEXTE light curves for each source and energy bands and obtained values ranging from 2% to as high as 18% with (Poisson) errors less than 0.5%. We obtain similar numbers for folded background light curves too! **This indicates that systematic effects dominate the folded light curves and all results from HEXTE should be interpreted very cautiously.** An analysis for obtaining the value of systematic errors is underway.
To claim a detection with HEXTE, one needs to show that the same pulse structure exists in both Cluster A and Cluster B, and the background does not show a similar structure. For 1E 1841−045, 1RXS J1708−4009, and 4U0142+61, the PCA folded light curves show very similar morphologies in the 6–15 keV and 15–30 keV band. Therefore, observation of a similar morphology in the HEXTE folded light curves above 30 keV could also be a strong indication for a detection. We note that this is not a requirement. 1E 1841−045 folded light curves in HEXTE fulfill both requirements, and also the shapes are consistent with the PCA light curves. The same is not true for the remaining sources. It is essential to have INTEGRAL observations off all AXPs to confirm any HEXTE detection (recently 4U 0142+61, and 1RXS J1708-4009 were also detected with IBIS, den Hartog et al. 2004), and also to be able to use HEXTE results with confidence.

References

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