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Article

A proposal to validate big data from RXTE satellite

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Abstract

The Proportional Counter Array (PCA) is the primary instrument on board of Rossi X-ray Timing Explorer (RXTE) satellite. It was operated for more than 16 years to detect the time variation of astronomical X-ray sources in the range of 2-60 KeV and provide event information timed to microseconds in different channels with different data modes. This variety makes it harder to analyze such huge data using the standard procedures. In this study, a customized software is proposed to validate the data by considering all necessary precautions before extracting the final lightcurves (LCs) which are used in both spectral and timing analyses. The proposed software is under test by reproducing the results of four well-known objects with (> 3,000 observations) and total exposure time (>5 million seconds). The results showed good agreement with the diagnostic diagrams from literature. However, this code is fast and applies all the standard procedures in one process using one interface.

Keywords

RXTE, PCA, Big Data, HEASoft, IDL.

1. Introduction

The Rossi X-ray Timing Explorer (RXTE) is a satellite that is devoted to study the temporal variability of X-rays sources with time scales from microseconds to months with moderate spectral resolution in the energy range 2-200 keV, see. (Glasser et al., 1994)

RXTE spacecraft was carrying three different instruments: (1) Proportional Counter Array (PCA), (2) All Sky Monitor (ASM), (3) High-Energy X-ray Timing Experiment (HEXTE). The Proportional Counter Array (PCA) is the primary instrument on-board of RXTE. It was operated to detect the time variation of astronomical X-ray sources in the range 2-60 KeV to provide event information timed to 1-microsecond in different channels with different data modes.

By the end of 1995, RXTE launched from on a Delta rocket and finally, it ceased science operations in January 2012 (more than 16 years). This long operation period and the variety of data files and datamodes make it harder to analyze such huge data using the standard procedures.

In this work, we introduce a proposed customized software in the IDL environment to validate the data and consider all these precautions before extracting the final lightcurves (LCs) which are used in both spectral and timing analyses. This software will be tested by reproducing the results of (>3,000 observations) from 4 well-known sources with total exposure time about

(>5 million seconds). This article is outlined as follow, in section (2) the PCA instrument is described in more details with clear explanation about structure, datafiles, datamodes, and configurations. In section (3), we introduce the proposed methodology and the algorithm to consider the standard procedures in the analysis. In section (4), the results are tested and discussed with 4 well-known sources. Finally, we conclude our results in section (5).

2. PCA Instrument

2.1 PCA Structure

PCA is a large area array of proportional counters which has been developed as the main instrument of the RXTE satellite. It is comprised of 5 independent detector units, each with a net viewing area of 1475 cm2 and filled with a mixture of [90%, and 10%] [Xenon, and Methane] gas respectively at 845 mm pressure and it is operating in the energy range of 2-60 keV to provide event information timed to 1-microsecond with spectral resolution of -18% FWHM at 6 keV, see table (1).

Each PCU is split into two volumes, the upper propane veto volume, and the main xenon volume. Through these volumes run five layers of anode-wire grids (1 propane veto; 3 xenon, each split into two; 1 xenon veto layer). The top layer is the most sensitive. Based on the configuration, the data files may contain either the signal summed from all PCUs or separate signals from one or more PCUs. The PCA team monitors the gain and offset values of the PCA energy-to-channel conversion by analyzing Standard-2 data which contain events from the on-board calibration source.

Table 1. Comparison between PCA and HEXTE instruments.

Instrument	PCA	HEXTE
Energy range	2 - 60	15-250
Collecting area	7000 cm2	2 x 800 cm2
Energy resolution	18% at 6 keV	15% at 60 keV
Time resolution	1 micro sec	8 microsec

2.2. PCA Datafiles

A. Science Array Files: this format is used for data binned at regular intervals by the spacecraft electronics. For example, PCA Standard-1 or Standard-2 configuration which contains 129-channel spectra accumulated every 16 seconds.

B. Science Event Files: this format is used for unbanned data, i.e., for individual events. An example is the PCA Good Xenon configuration which contains time-stamped events with 256-channel resolution, PCU ID and anode ID.

2.3. Configurations and Datamodes

According to the purpose of the calculation and data reduction, some decisions should be taken regarding data selection. Thus, we will explain different configuration and datamodes to explain the reason for different reduction methods.

The mode is a broad scheme for packaging PCA data, while the configuration is the specific implementation of the mode. There are 7 Experiment Data System (EDS) modes in different configurations. In fact, as a general rule, data in different configurations - even of the same mode - should not be reduced together. The Experiment Data System (EDS) has 8 Event Analyzers (EAs), 6 devoted to the PCA and the other 2 are for the ASM. Each EA sees all the PCA data just as if the original incoming data stream were duplicated five times. Each EA can run in any of 7 basic "modes" which are further defined and tuned by a set of parameters (such as energy bin boundaries).

The implementation of a mode with specific parameters is known as a "configuration". Understanding how the configuration determines the format of your data is very important and is discussed below. Always 2 of the EAs run in the "Standard-1" and "Standard-2" configurations. The other 4 EAs run in configurations specified by the observer.

RXTE provides unprecedented true microsecond timing resolution and covers a broad energy range. (Bradt et al., 1993) The PCA observations were made consistently with the following set of data modes. (Morgan, 1994) a binned mode with 4 ms time bin and 8 energy bands in the range of 2-13.1 keV; an event mode with (16 µs) time bin and 16 energy bands above 13.1 keV; and two single-bit modes with (122 ks) time bin, covering the energy bands 2-6.5 keV and 6.5-13.1 keV, respectively, as well as good xenon mode with the best time binning and 256 energy bands. Therefore, to cover the full energy band it might be possible to use one mode or to combine two different modes e.g., event mode plus binned or single-bit modes.

3. Methodology

The aim of this work is to introduce proposal to analyze big data from PCA to study the timing and spectral properties of 4-selected well-known sources by extracting reliable LCs with different time resolution in different energy bands. It is worth to assert that again, this sort of analysis should not be thought of as a simple recipe; rather, it is an analysis technique that requires to make several decisions based on the scientific priorities of the investigation and on the properties of the source.

3.1. Validation Algorithm

The aim of this proposal is to study the temporal and spectral properties of sources by generating LCs with different time resolutions in different energy bands. Consequently, the time binning and energy band are the main criteria to select input datafiles.

However, it is not an easy task to find datafiles that fulfil these criteria, because PCA/RXTE has different datamodes (event, binned, and single-bit) in different energy bands and different time resolutions. So that, the LC extractor may use more than one input datafile/datamodes to cover the full energy band and the full exposure time of the observation. Consequently, the importance of introducing this proposal is that all procedures (starting from downloading the data through data validation and selection) can be done automatically.

In the beginning, the code is used to download list of all available data for selected sources. Then, the data from PCA archive are validated by applying (4-tests) to select reliable data and exclude others that do not fulfil these 4-requirements:

1. Good Time Interval (GTI) is defined to apply the standard screening criteria,
2. Minimum exposure time is defined to exclude short observations.
3. Channel range which is defined according to the purpose of the work, and
4. Time binning (tb) of the input datafiles.

Briefly, the algorithm of the 4-tests code is used to check the input criteria of each observation according to [GTIs, time resolution, full channel range, and minimum exposure time]. Then, it selects the final list of datafiles based on the required criteria for this analysis, in addition, it shows printouts of datafiles and datamodes that included and excluded before and after applying each test; so that, it is easy to check the excluded datafiles from the input list.

There are two different approaches to extract clean LCs. First, to filter and clean the raw data before extracting LCs, but it is not an easy task. The second approach, which we used here, is to apply the criteria and extract clean LCs in one run using (*FTOOLS*) or Binlc (IDLX) from Markwardt's (*IDLX*) library. For each calculation, some decisions should be taken regarding the extracted LCs: (time bin-size, exposure time, time start, time stop, GTIs, energy intervals, channel ranges, etc.). Hence, this software is proposed to accomplish these tasks automatically where the datafiles are investigated and selected according to the purpose of the calculations.

This flexibility of applying different criteria facilitates the purposes of our work to extract varieties of LCs, with different time resolutions and energy bands, thus we can analyze the data using different techniques and test the limitations of the available data on PCA/RXTE.

4. Results

Following the standard procedures described in the algorithm to analyze sample of sources, we selected 4 well-known objects that show wide range of variability with bright outbursts: two Black Holes (BHs): (GX_339-4, and H_1743-322), and two Neutron Stars (NSs) (Aql_X-1, and 4U_1608-52). The data in the course of this study are available in the NASA's Archive High Energy Astrophysics Science *Archive* Research Center, under the Archival/proprietary (*HEASARC*) PCA data.

For count rate (CPS) calculations, the average count rate of the source and the background are extracted from the standard-2 datafiles for each observation using only PCU2 in the channel range: 0-35 (2-15 keV). Then, the source is subtracted from its background in the same energy band. It is important to notice that the data is collected from different epochs, which in turn change the channel-energy relationship for the data, hence, this should be considered in each outburst of the analyses, see (*Energy-Channel Conversion Table*).

For hardness ratio (HRR) calculations, the average count rates are extracted from standard-2 datafiles using only PCU2 in two different bands: in the channel ranges: 16-35 (6-15 keV), and 0-15 (2-6 keV), for hard and soft bands, respectively. Then, the hardness ratio parameter is calculated by dividing the count of hard band over the count rate of the soft bands, after subtracting the background of each band.

For RMS (Root Mean Square), we followed the standard procedures described in the literature to produce Power Spectral Densities (PSDs) and calculate RMS, see. (T. Belloni et al., 2000; BELLONI & HASINGER, 1990; T Belloni & Hasinger, 1990; Tomaso Belloni et al., 2002; Churazov et al., 2001; Klis, 1989; Leahy et al., 1983; Lewin et al., 1988; Miyamoto et al., 1991, 1992; Miyamoto & Kitamoto, 1989; M. A. Nowak, 2000; Michael A. Nowak et al., 1999; K. Pottschmidt et al., 2003; K Pottschmidt et al., 2000, 2001; Katja Pottschmidt et al., 1998; van Straaten et al., 2002; Vaughan et al., 1994)

In our work, we selected only 3 outbursts from each object as following: for GX_339-4, we selected 3 among 4 full outbursts: (2002), (2007), and (2007). For H_1743-322, we selected 3 among 5 full outbursts: (2003), (2009), and (2010). For Aql_X-1, we selected 3 among 4 full outbursts: (1999), (2000), and (2011). For 4U_1608-52, we selected 3 among 5 full outbursts: (2002), (2005), and (2007). Now the final lists of observations are ready for investigations, see table (2).

Table 2. It shows the total number of observations, and exposure time for all objects before and (after)* applying the (4-tests) criteria.

Object Name	Type	Exposure* (ks)	Observations*
GX 339-4	BH	(1250)	1402 (905)
H_1743-322	BH	(936)	541 (325)
Aql X-1	NS	(1588)	591 (561)
4U 1608-52	NS	(1777)	1102 (848)
Total	4 objects	(5551)	3636 (2639)

* Note: the numbers in parentheses mean that the (4-tests) criteria are applied.

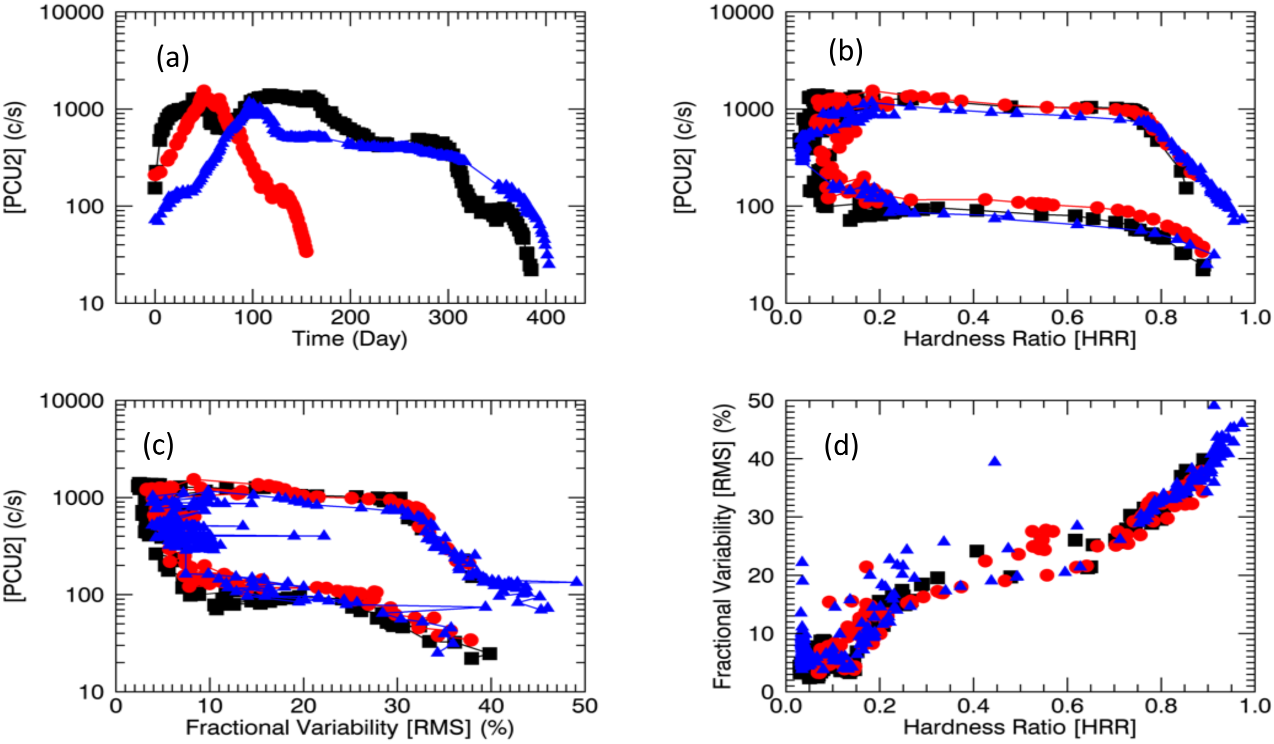

Figure 1. The diagnostic diagrams (long LC, HID, RID, & HRD) are shown in panels (a-d), respectively, for 3 outbursts from (GX339-4): 2002 (black squares), 2007 (red circles), and 2010 (blue triangles).

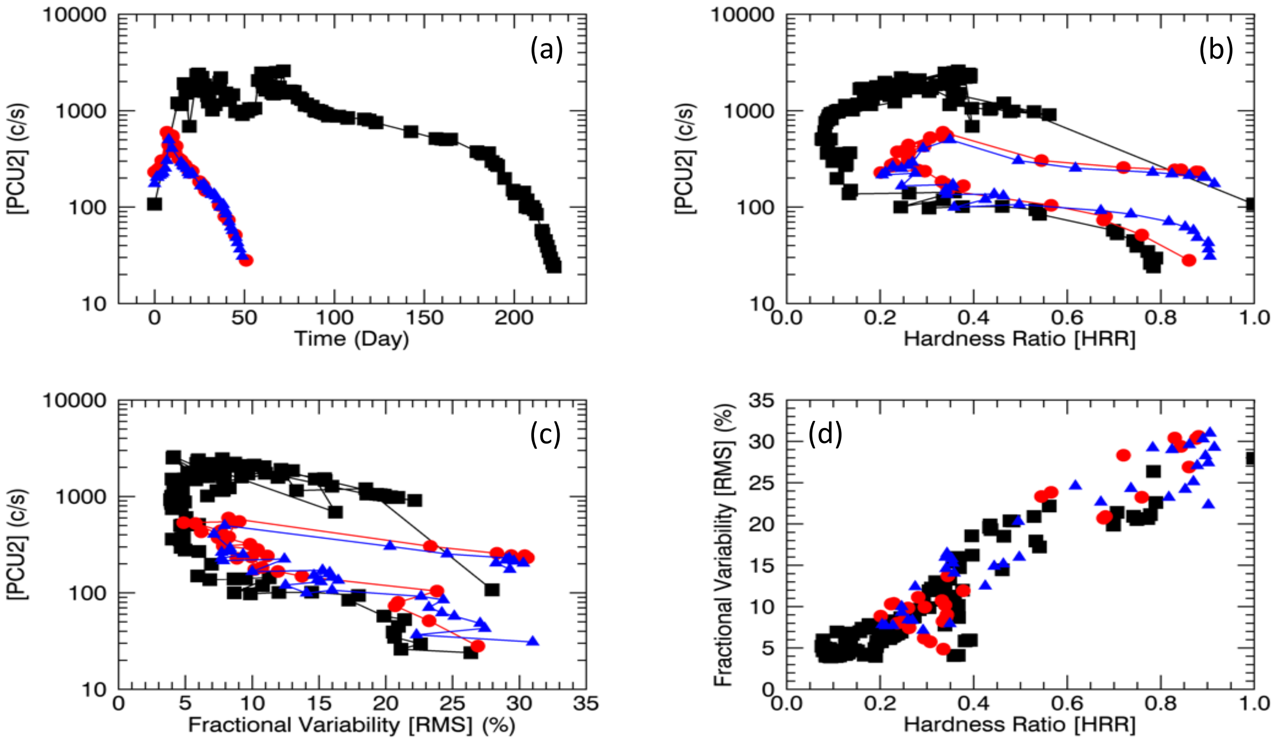

Figure 2. The diagnostic diagrams (long LC, HID, RID, & HRD) are shown in panels (a-d), respectively, for 3 outbursts from (H1743-322): 2003 (black squares), 2009 (red circles), and 2010 (blue triangles).

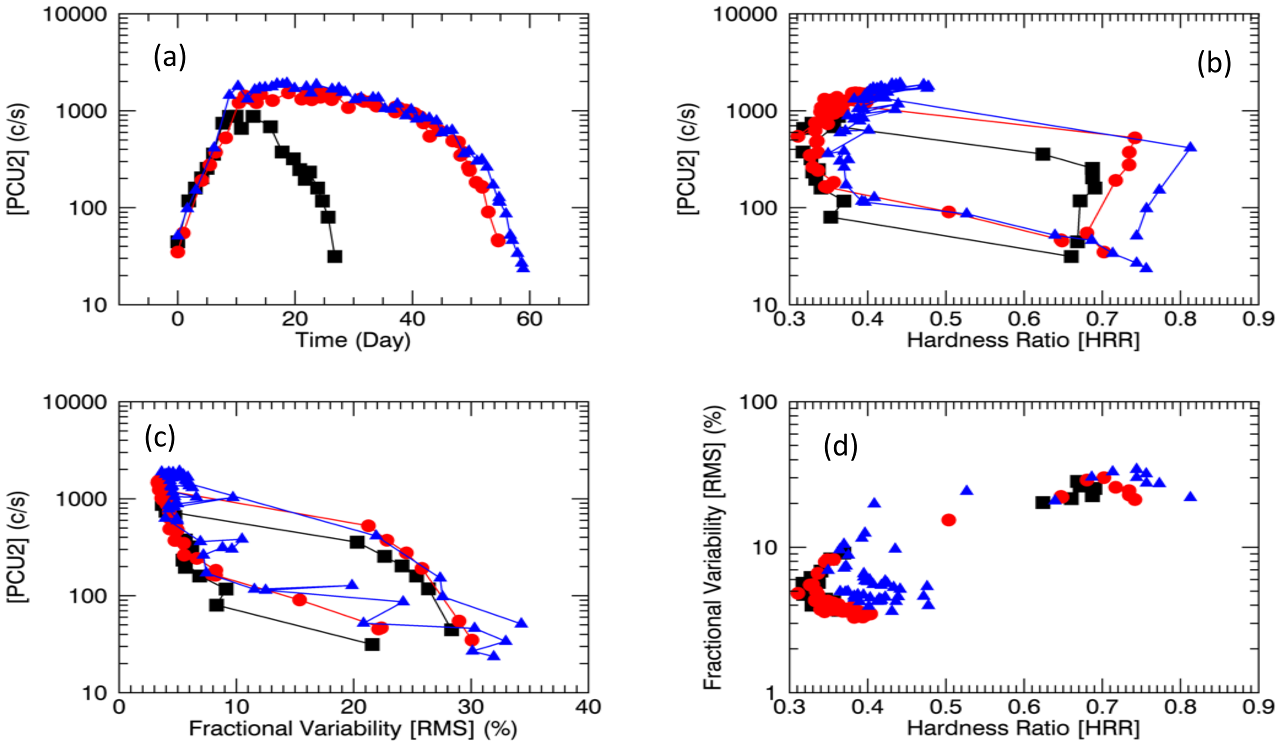

Figure 3. The diagnostic diagrams (long LC, HID, RID, & HRD) are shown in panels (a-d), respectively, for 3 outbursts from (Aql_X-1): 1999 (black squares), 2000 (red circles), and 2011 (blue triangles).

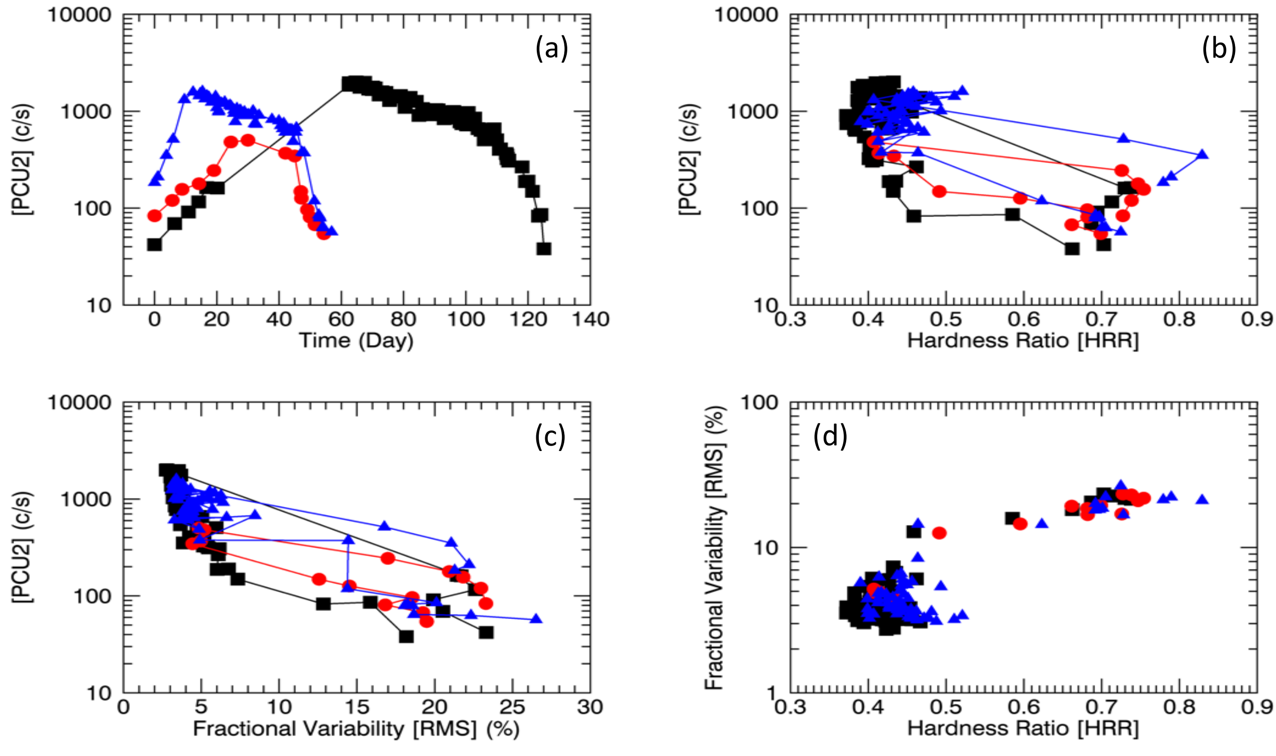

Figure 4. The diagnostic diagrams (long LC, HID, RID, & HRD) are shown in panels (a-d), respectively, for 3 outbursts from (4U1608-52): 2002 (black squares), 2005 (red circles), and 2007 (blue triangles).

Table (2) summarize the total number of observations 3636 (2639) for all sources before and (after) applying the 4-tests criteria; as following: 1402 (905), 541 (325), 591 (561), 1102 (848) for sources: GX_339-4, H_1743-322, AQL X-1, and 4U_1608-52; respectively. Also, it shows the total exposure time (5551) ks for all sources (after) applying the 4-tests criteria; as the following: (1250), (936), (1588), and (1777) ks; respectively.

Figures (1-4) show the diagnostic diagrams for 4 objects [GX_339-4, H_1743-322, AQL X-1, and 4U_1608-52], respectively. Panels (a) show the evolution of average count rates (long LC) from PCU2 only. Panels (b) show correlation between the hardness and count rate parameters, and it is known as Hardness Intensity Diagram (HID). while panels (c) show the correlation between RMS and count rate parameters, and it is known as RMS Intensity Diagram (RID). Panels (d) show the correlation between Hardness and RMS parameters in the Hardness-RMS-Diagram (HRD). In each panel, there are 3 outbursts are shown for each object where each point represents one observation.

5. Discussion

For the BH-Transient (GX_339-4), the code retrieves all available data (1402 observations) from the archive. Then, it validates (905) observations with exposure time (1250) ks. Finally, we could identify four outbursts (2002, 2004, 2007, and 2010) that show complete hysteresis loops, see figure (1). This is very similar to the results in the literature. (T. M. Belloni & Motta, 2016; Motta et al., 2011; Muñoz-Darias et al., 2011)

For the BH-Transient (H_1743-322), the code retrieves all available data (541 observations) from the archive. Then, it validates (325) observations with exposure time (936) ks. Finally, we could identify five outbursts (2003, 2008, 2009, 2010, and 2011) that show complete hysteresis like behavior, see figure (2). That is also very similar to the results in the literature. (Chen et al., 2010; Zhou et al., 2013)

For the NS-atoll (Aql_X-1), the code retrieves all available data (591 observations) from the archive. Then, it validates (561) observations with exposure time (1588) ks. Finally, we could identify five outbursts (1999, 2000, 2004, 2009, and 2011) that show complete hysteresis like behavior, see figure (3). Clearly, this is very similar to the results in the literature. (Maitra & Bailyn, 2004; Muñoz-Darias et al., 2014)

For the NS-atoll (4U_1608-52), the code retrieves all available data (1102 observations) from the archive. Then, it validates (848) observations with exposure time (1777) ks. Finally, we could identify five outbursts (2002, 2005, 2007, 2010, and 2011) which show complete hysteresis loops, see figure (4). Again, this is very similar to the results in literature. (Muñoz-Darias et al., 2014)

Clearly, the results of this proposed software show great agreement with the literature for the characteristic parameters (CPS, HRR, RMS) and the diagnostic diagrams (LTS, HID, RID, and HRD). Hence, this code is very efficient proposal that can be used to validate and analyze the big data from RXTE/PCA, however it is still under test and need to be developed to do all calculations according to the standard precautions and it should be tested in very large scale to identify full outbursts.

6. Summary and Conclusion

The PCA is the primary instrument on-board of (RXTE) which was operated for 16 years to detect the time variation of astronomical X-ray sources. The PCA provides event information timed to microseconds in different channels with different data modes. This variety makes it harder to analyze such huge data using the standard procedures. The aim of this work is to introduce proposal to analyze big data from PCA by studying timing and spectral properties of four well-known sources objects with (> 3,000 observations) and total exposure time (>5 million seconds) to extract reliable LCs with different time resolution in different energy bands.

The time binning and energy band are the main criteria to select the input datafiles according to the analysis purpose. However, it is not an easy task to find datafiles that fulfil these criteria, because PCA/RXTE has different datamodes (event, binned, and single bit) in different energy bands and different time resolutions. Hence, the light curve extractor may use more than one input datafile/datamodes to cover the full energy band and the full exposure time of the observation.

Therefore, a customized code (in IDL environment) is proposed to automatically accomplish all tasks. First it is used to download the list of observations from the RXTE/PCA archive. Then, the algorithm of the (4-tests) code is used to select reliable data and exclude others according to [GTI screening criteria, the minimum exposure time, the time binning, and the energy]. Hence, the datafiles and datamodes can be validated and selected automatically according to customized input criteria. This flexibility of applying different criteria facilitates the purposes of our work to extract varieties of LCs, with different time resolutions and energy bands.

Following the standard procedures described in the literature, RMS, CPS, and HRR are calculated for four well-known objects which are selected to show wide range of variability with bright outbursts: two Black Holes (BHs): (GX_339-4, and H_1743-322), and two Neutron Stars (NSs) (Aql_X-1, and 4U_1608-52).

The results confirmed that full outbursts show hysteresis like behavior in HID, and RID diagrams. So that, we could identify (5) full outbursts in H_1743-322, (4) full outbursts in GX_339-4, (5) full outbursts in 4U_1608-52, and (5) full outbursts in Aql_X-1. These identified outbursts are the same to what found in the literature.

Only three outbursts are selected as sample to study each source with total number of observations 3636 (2639) for all sources before and (after) applying the 4-tests criteria, respectively, and the total exposure time is (5551) ks for all sources (after) applying the 4-tests criteria.

Figures (1-4) show the results in four panels where each point represents one observation. Top left panel shows the evolution of average count rates from (PCU2) only. Top right and bottom left panels show (HID), and (RID); respectively. Bottom right panel shows the correlation between Hardness and RMS parameters in the Hardness-RMS-Diagram (HRD).

Clearly, the results of this proposed software show great agreement with the literature for the characteristic parameters (CPS, HRR, RMS) and the diagnostic diagrams (LTS, HID, RID, and HRD). Hence, this code is very efficient proposal that can be used to validate and analyze the big data from RXTE/PCA, however it is still under test and need to be developed to do all calculations according to the standard precautions and it should be tested in very large scale to identify full outbursts.

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الملخص العربي

مقترح لتنقيح البيانات الضخمة من القمر الصناعي RXTE

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يعتبر الكاشف التناسبي (PCA) هو أحد الأجهزة الرئيسية التي تستخدم على متن القمر الصناعي (RXTE). وهي المهمة التي ظلت تعمل لمدة تزيد عن ١٦ عام متتالية لدراسة الاجرام السماوية في نطاق اشعة اكس عن طريق فحص التغيرات الزمنية والطاقية في مدي (٢-٦٠) كيلو إلكترون فولت والذي يغطي احداث زمنية في حدود الميكرو ثانية في العديد من القنوات المختلفة حسب الطاقة وكذلك طريقة حفظ وارسال الملفات (datamodes). كل هذه الاختلافية جعلت تحليل مثل هذه البيانات الضخمة باستخدام الطرق القياسية مهمة صعبة. في هذه الدراسة نقدم مقترح لتطبيق كل هذه الخطوات القياسية لاستخلاص المنحنيات الضوئية (LCs) والتي تستخدم في كل من التحليلات الزمنية والطيفية. حيث سيتم وضع المقترح تحت الاختبار على مجموعة من البيانات الضخمة (أكثر من ٣,٠٠٠ رصدة) والتي تم رصدها من (٤) مصادر معروفة ومتنوعة، ليصبح المجموع الكلي لزمن الرصد ما يزيد عن (٥ مليون ثانية). وقد أظهر المقترح نتائج دقيقة يمكن الاعتماد عليها ومن هنا تأتي أهمية هذا البرنامج للتعامل مع البيانات الضخمة بسرعة عالية لتطبيق كافة المعايير الأساسية وباستخدام نافذة واحدة.