PROCEEDINGS OF SCIENCE

4U 1630-47 during 2002-2006 outburst activity - Timing analysis

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The X-ray transient 4U1630-47 shows regular outbursts with a recurrence period of 600 days since its first detection by Vela-5B in 1969. RXTE/ASM monitor reveals heightened activity during 2002 - 2004 and in beginning of 2006. During these periods, the *RXTE*/PCA observed the source when it was in different stages of the outburst. Detailed spectral and timing analysis had been carried out with the data. Spectral analysis showed the presence of high temperature states as they were reported by Tomsick et al (2005). Detailed timing analysis presented in this work revealed that the quasi-periodic oscillations (QPOs) are present only in the high temperature states. The variation of inner disk radius with inner disk temperature for high temperature states shows a distinct pattern in $T_{in} - R_{in}$ plane as compared to the one expected from a standard Shakura-Sunyaev disk. This may possibly indicate the presence of a slim disk.

VI Microquasar Workshop: Microquasars and Beyond
September 18-22 2006
Società del Casino, Como, Italy

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PoS(MQW6)070

1. Introduction

The X-ray transient (XRT) $4U1630-47$ shows regular outbursts approximately every 600 days since its discovery ([2], [10], [4]), which is much more frequent as compared to other soft X-ray transients which flare once in $10-50$ years [11]. Therefore $4U1630-47$ plays an important role in studying the dependence of the observed spectral and/or timing properties upon mass accretion rate and other physical parameters. Since the optical counterpart is not known for $4U1630-47$ [7] (see [1] for possible identification of IR counterpart), the binary orbital period is unknown. Its X-ray spectral and timing properties are typical of low-mass X-ray binaries with black hole as a probable compact object [11].

During 2002-2004, $4U1630-47$ exhibited the longest and also the brightest outburst observed to date and thereafter it was again active in early 2006. Unlike a previous outburst in 1998, during this outburst no radio emission was seen. Tomsick et al (2005) carried out a detailed spectral analysis of the data during 2002-2004. The main result of their work was that they reported different spectral states of the source during the outburst. They also reported some extreme states with very high inner disk temperatures and small inner disk radii. Interestingly those states were found to be very high states with steep power-law component in the spectra. Here in this work we studied the spectral and timing properties and their possible correlated behavioural pattern of the source during the outburst. For spectral modelling, we considered a reflection component coming from cold disk in addition to the standard two-component model used by Tomsick et al (2005) in order to get better (or physically plausible) estimate of inner-disk temperatures.

2. Observation and Data Analysis

We analysed $RXTE$ PCA data of 330 pointed observations of the X-ray transient $4U1630-47$ during its various phases of outbursts in 2002-04 and in 2006. Figure (1) shows the $RXTE$/ASM lightcurve covering the complete stretch. The bars in red colour at the top of the figure indicate epochs when the PCA and HEXTE onboard $RXTE$ observed the source, while the bars in blue show the epochs when quasi-periodic oscillations (QPOs) were detected. The mean exposure time of the data is ~ 1.6 ks. FTOOLS version 5.3.1[1] was used to extract the lightcurves and energy spectra from the raw data. The time filtering criteria used in our analysis were same as those used by Tomsick et al.(2005) [12]. We extracted the lightcurves from event mode data for energy bands 2-7 keV, 7-15 keV, 15-30 keV and the complete energy band, with the time resolution of 2^{-8} sec. We extracted the energy spectra for all observations from standard2 data of the $RXTE$/PCA.

3. Spectral Analysis

Using the XSPEC (v11.3.1) package[2], we fitted the PCA spectra for all the observations with a single three-component model which consists of disk blackbody dominating at lower energies, a power law at higher energies and reflection of the power law component from the disk, along with interstellar absorption. Here, we used the reflection component to account for the broad excess

[1] http://heasarc.gsfc.nasa.gov/lheasoft

[2] http://heasarc.gsfc.nasa.gov/lheasoft/xanadu/xspec/index.html

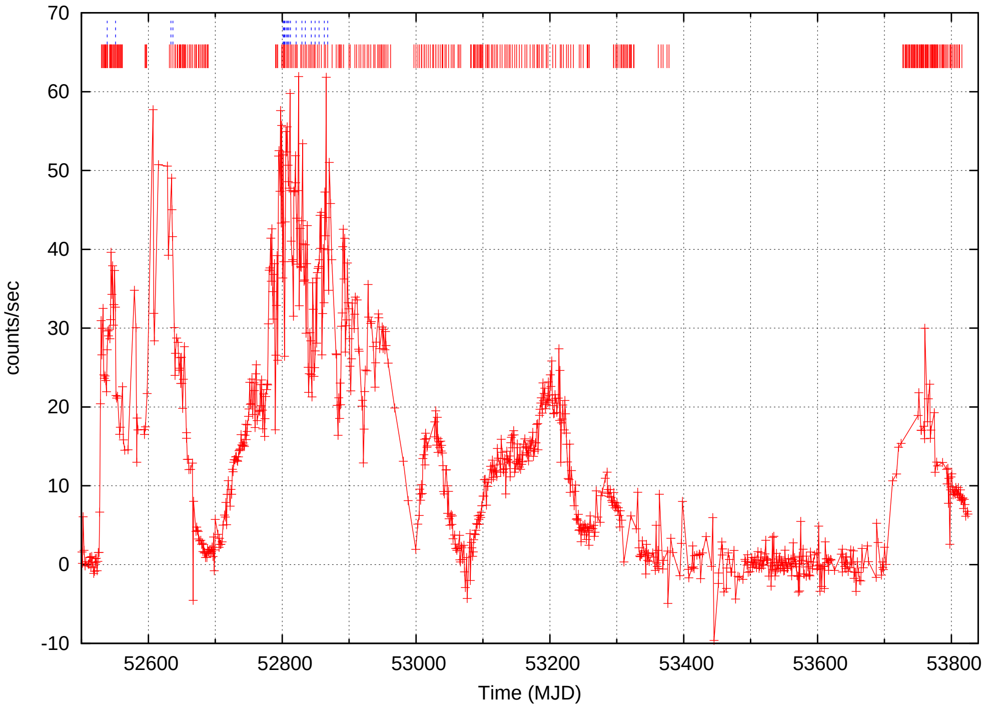

Figure 1: ASM 1-day averaged lightcurve starting from October 2002 up to March 2006. Red bars on the top show the epoch of the pointed observations by PCA and HEXTE on-board *RXTE* and blue bars show the observations when QPOs are detected.

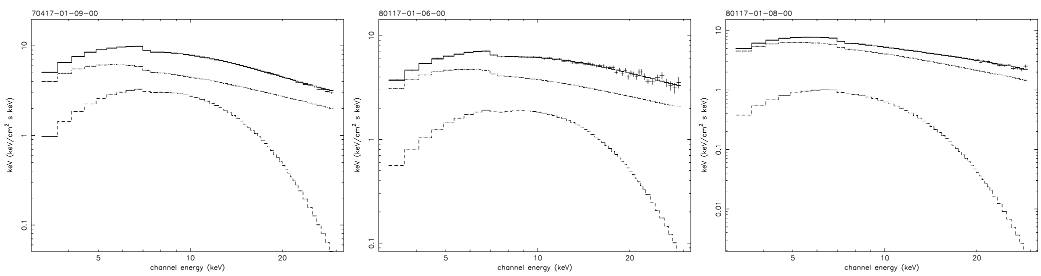

Figure 2: Un-folded spectra from three observations where QPOs were present; Obs.Ids.(MJD)[*from left*]: 70417-01-09-00(52636.8), 80117-01-06-00(52802.8) and 80117-01-08-00 (52810.1)

around 10 keV for some observations and hence to have a better estimation of the disk temperature in the *diskbb* model. For all the observations, the lower limit for the column density parameter (N_H) was restricted to $6 \times 10^{22}\ cm^{-2}$ which is the lowest measured value for $4U1630-47$ [8] and the source of reflection was assumed to be isotropic. Following the X-ray dips study [5], we have used 60^o as disk inclination angle.

We obtained statistically good fits for almost all the observations with average $\chi^2_\nu = 1.48$ while fitting the model to PCA spectra from $3-30$ keV using the χ^2-minimization algorithm of the XSPEC package. For the complete set of observations considered, the fitted value of disk temperature varies from 0.7 keV to 3.2 keV, while the power-law index varies from 1.5 to as steep as 4.8 . For three representative observations spanning the extreme spectral variability of the source when the QPOs were present, the un-folded spectra are shown in figure (2).

As per the classification scheme of spectral states of black hole binaries given by McClintock and Remillard (2006)[6], 92 observations are in steep power-law (SPL) state, 110 observations show thermal-dominated (TD) states while no observation exhibit hard state. Some states did have power-law index less than 2.0, but they could not be classified as hard states since for them the ratio of power-law flux to disk blackbody flux is small unlike a canonical hard state spectrum. Even with the reflection component, we got higher disk temperatures for few observations as reported by Tomsick et al.(2005)[12]. Interestingly, these high temperature states exhibit strong QPOs as discussed in the next section.

Figure (3) shows the variation of inner disk radius (R_{in}) as a function of the disk temperature (T_{in}). It shows four distinct branches in $R_{in} - T_{in}$ plane. Two parallel branches (represented by red points) can be fitted with the empirical relation, $R_{in} \propto T_{in}^{-4/3}$, which is clearly a signature of the standard Shakura-Sunyaev thin disk [3]. But the other two parallel branches (shown in blue) which correspond to high temperature QPO states is fitted with a relation $R_{in} \propto T_{in}^{-4}$. This could possibly be interpreted as an indication of a hot slim disk [13] which could be present during state transitions.

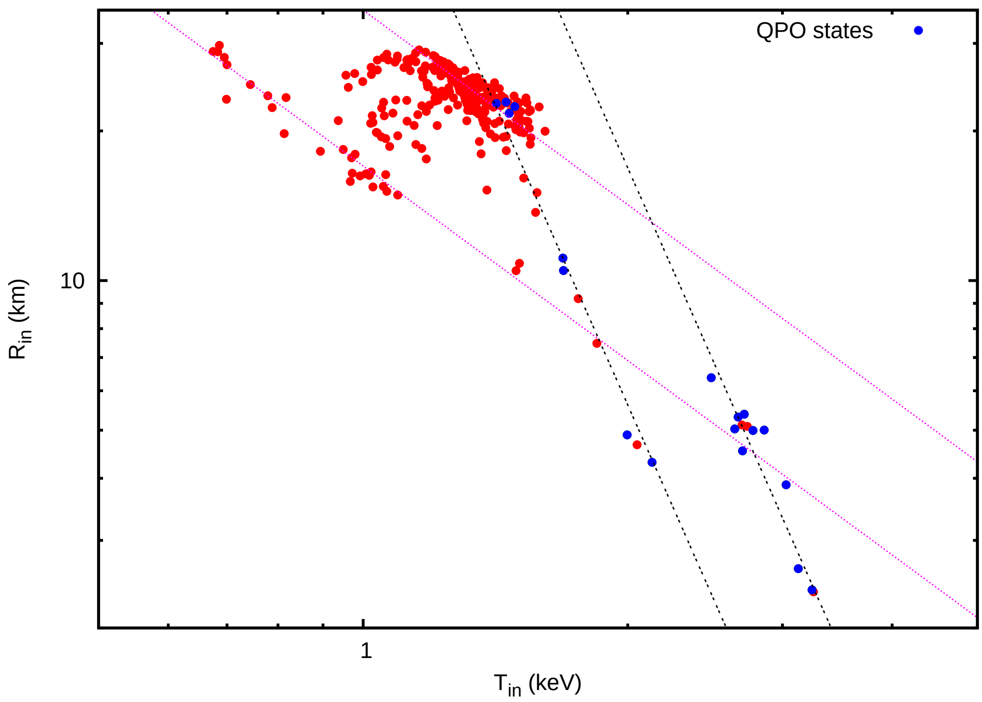

Figure 3: Plot of inner disk radius R_{in} versus disk temperature T_{in} for for all the observations. Blue dots show the QPO states. Two sets of parallel lines show two different dependences; magenta – $R_{in} \propto T_{in}^{-4/3}$ and black – $R_{in} \propto T_{in}^{-4}$.

4. Timing Analysis

We extracted the power density spectra (PDS) for all the observations using the ISIS package[3] and an add-on module called SITAR.[4] But we found one or more statistically significant QPOs for only 18 observations. During all these observations, the source was in steep power-law (SPL) state and also most of them exhibit high inner-disk temperatures. Possibly due to lack of sufficient data length, few other high temperature SPL observations do not show statistically significant QPOs. All these 18 power density spectra (PDSs) were fitted with a single model comprising of a zero frequency-centered Lorentzian(zfc) and four lorentzians, as defined below;

$$zfc = \frac{R_0}{1+\nu/\nu_0} \qquad \text{and} \qquad Lor = \pi^{-1}\frac{R^2 Q \nu_0}{\nu_0^2 + Q^2(\nu-\nu_0)^2}$$

where in the Lorentzian component, ν_0 is the resonant frequency of the Lorentzian, Q $(= \Delta\nu_0/\nu_0$, where $\Delta\nu_0$ is FWHM of the Lorentzian at $\nu_0)$ is the quality factor and R is the normalization of the Lorentzian, such that rms variability, $rms = R[0.5 - tan^{-1}(-Q)/\pi]^{1/2}$ (i.e. $rms = R$ as $Q \to \infty$).

For the three observations whose energy spectra are shown in figure (2), the PDSs with the fitted multi-component model are shown in figure (4). All the parameters for all 18 PDSs are given in Table (1) and Table (2) which are attached separately. We tried to find any correlation of QPO parameters with the spectral parameters of the state but no significant correlation was found from the set of observations.

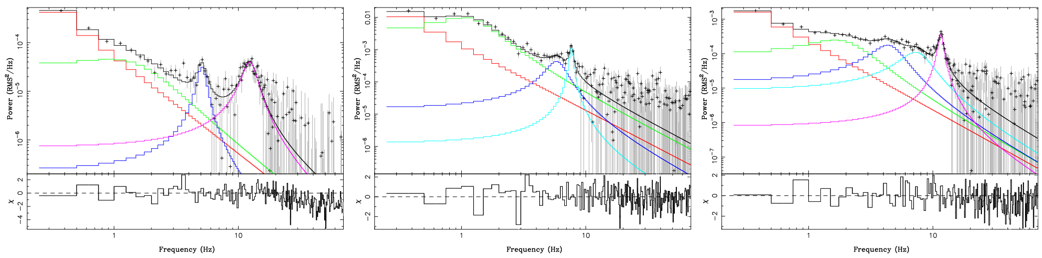

Figure 4: PDSs for the three observations whose un-folded energy spectra are shown in figure (2). The components of the fitted model(*described in the text*) are shown in different colours.

5. Conclusion

We have analysed RXTE *PCA* data of 4U 1630-47 during 2002-04 and in 2006 when the source was in outburst and have carried out spectral and temporal analysis of the data. We fitted the energy spectra of all these observations with a single three-component model. Here, we have taken into account the reflection from the cold disk in order to account for the hardening above 10 keV [9], which was may cause high values of disk temperatures as reported by Tomsick et al.(2005)[12]. Still, those spectral states had high temperatures and small inner disk radii as compared to the standard Shakure-Sunyaev disk. Following the state classification of black hole binaries of McClintock

[3]http://space.mit.edu/CXC/ISIS

[4]http://space.mit.edu/CXC/analysis/SITAR

and Remillard [6], these high temperature states fall in the category of SPL states. The calculated inner radius (R_{in}) and inner disk temperature (T_{in}) show two distinct trends - one corresponding to the standard Shakura-Sunyaev disk with low temperature and the other trend, mainly consisting of high temperature states. Interestingly, these high temperature states which are very high states with steep power-law exhibit low frequency QPOs in their PDSs. Though, no significant correlation is found between the QPO parameters and the spectral parameters. As these states follow a different trend in $T_{in} - R_{in}$ plane as compared to the ones corresponding to Shakura-Sunyaev disk, they indicate the presence of slim disk [13]. Hence, very high disk temperatures in these states can be the artifact of using DBB model for slim disk states as discussed by Watarai et al.(2000) [13].

6. Acknowledgement

This research has made use of data obtained from the High Energy Astrophysics Science Archive Research Center (HEASARC), provided by NASA's Goddard Space Flight Center. Authors acknowledge Manojendu Choudhury for valuable discussions and M. Nowak for his extended support in using ISIS package for timing analysis.

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