Studies of Quasi-Periodic Oscillations in the Black Hole Transient XTE J1817-330

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ABSTRACT
We have used archival RXTE PCA data to investigate timing and spectral characteristics of the transient XTE J1817-330. The data pertains to 160 PCA pointed observations made during the outburst period 2006, January 27 to August 2. A detailed analysis of Quasi-Periodic Oscillations (QPOs) in this black hole X-ray binary is carried out. Power density spectra were obtained using the light curves of the source. QPOs have been detected in the 2-8 keV band in 10 of the observations. In 8 of these observations, QPOs are present in the 8-14 keV and in 5 observations in the 15-25 keV band. XTE J1817-330 is the third black hole source from which the low frequency QPOs are clearly detected in hard X-rays. The QPO frequency lies in $\approx 4-9$ Hz and the rms amplitude in 1.7-13.3% range, the amplitude being higher at higher energies.

We have fitted the PDS of the observations with Lorentzian and power law models. Energy spectra are derived for those observations in which the QPOs are detected to investigate any dependence of the QPO characteristic on the spectral parameters. These spectra are well fitted with a two component model that includes the disk black body component and a power law component. The QPO characteristics and their variations are discussed and its implication on the origin of the QPOs are examined.

Key words: stars: black hole binary: individual: XTE J1817-330 stars

1 INTRODUCTION

Accretion powered X-ray binaries are the brightest X-ray sources in our Galaxy. These binaries contain either an accreting neutron star or an accreting black hole as the X-ray source. Based on estimates of the mass of the accreting object and its X-ray characteristics, about 40 X-ray sources have been classified as black hole binaries (Remillard and McClintock 2006a). Of these 20 have reliable mass estimates and are, therefore, regarded as confirmed black holes while the remaining 20 are considered to be black hole candidates (Remillard and McClintock 2006a). A majority of the black hole binaries (BHBs) are transients and most of them have a low mass optical companion.

The black hole X-ray binaries have several distinctive X-ray characteristics. During the outburst there is a strong soft component that originates in the inner region of the hot accretion disk. The presence of a hard X-ray component in energy spectra is another common feature of black hole binaries. The hard X-rays arise through Compton scattering of low energy photons from the accretion disk in a hot optically thin plasma. The resulting hard X-rays are referred to as the thermal Compton component (McClintock and Remillard 2006).

Low frequency quasi-periodic oscillations (QPOs) in $\approx 0.1-40$ Hz range and high frequency QPOs $\approx 50-450$ Hz also occur in many BHBs. Presence of several distinct spectral states and transition from one state to another at irregular intervals, is another distinguishing feature of BHBs. Spectral and temporal characteristics of the sources vary from one state to another. Remillard and McClintock (2006a) have broadly classified the spectral state for BHB as (a) High or Soft state (HS) dominated by the thermal component, (b) Low or Hard State (LH) marked by the hard X-ray power law and (c) Steep power law (SPL) or very high state characterized by steep slope power law component. For a more complete description of the spectral states McClintock and Remillard (2006) included two more states namely an Intermediate state (IM) that occurs when the source moves from LH to HS state and an extreme LH state which they called as quiescent state. Gierlinski, Done and Page (2008) have included an additional state termed as
Ultra soft state (US) which is an extreme case of high/soft state found in this source. The US state is characterized by a very weak high energy tail with a low disk temperature and very low hardness ratio $\lesssim 0.1$ (Gierlinski, Done and Page 2008). The low frequency QPOs are usually detected in the SPL and LH states and have been observed in 14 BHBs so far (Remillard and McClintock 2006a). Detection of LFQPO in XTE J1817-330 indicates that LFQPOs can also be found sometime in the HS state.

An X-ray transient known as XTE J1817-330 was discovered by Remillard et al. (2006b) on 2006 January 26, with the All Sky Monitor (ASM) on Rossi Timing X-ray Explorer (RXTE) (Levine et al. 1996). At the time of its detection the $2-12$ keV flux was 0.93 Crab. The intensity then rose to a peak value of 1.9 Crab on January 28, and then declined to 1.2 Crab by January 30. Subsequently it decayed exponentially with a decay time of 27 days (Sala et al. 2007). From its high/soft state at the time of the outburst, the source declined to a low/hard state characterized by $kT = 0.2$ keV. A change in the intensity state of the source occurred around $\sim$ February 9 (Shaw et al. 2006). Hard X-rays (20-60 keV) flux increased from 46 $\pm$ 2 mCrab on February 9 to 79 $\pm$ 2 mCrab on February 14 accompanied by a decrease of soft X-ray (2-10 keV) flux from 840 $\pm$ 4 mCrab to 670 $\pm$ 4 mCrab during this period indicating the onset of the hard state (Kuulkers et al. 2006).

Its energy spectrum was studied with the RXTE, XMM-Newton, Integral and Swift instruments. Sala et al. (2007) measured the spectra using data from the XMM-Newton and Integral instrument when the source was in a high/soft state during 2006 February-March. Their spectral results indicated that its energy spectrum was typical of a BHB source with a dominant thermal disk component well described by $kT \sim 0.7-0.9$ keV and a thermal Compton power law component with a photon index of $\sim 2-3$ (Sala et al. 2007). Its spectral characteristics were observed with X-ray telescope (XRT) on the Swift satellite covering different stages of the outburst over 160 days. During this period the source made transition from the high/soft state in the initial outburst to a low hard state near the end of the outburst. The XRT spectra in the high soft state in 0.6-10 keV are well described to a low hard state near the end of the outburst (Rykoff et al. 2007).

A detailed study of the spectral evolution of XTE J1817-330 at different phases of the outburst was carried out by Gierlinski, Done and Page (2008) using the RXTE and the Swift data. The spectra of 150 PCU2 (RXTE) observations were modeled with the two component spectral model consisting of a disk component and a hard thermal Compton power law component. Using the same XRT data as used by Rykoff et al. (2007), they also found that the inner disc temperature declined from $\sim 0.9$ keV to $\sim 0.2$ keV as the source intensity declined. Based on this they claimed that the accretion disk recedes when the source transits from the high/soft state to the low/hard state.

It may also be noted that apart from XTE J1118+480, this black hole binary has the lowest absorption along the line of sight among all the bright black hole candidates as obtained from the Chandra and Swift spectral data (Miller et al. 2006a,b).

Power density spectra of XTE J1817-330 obtained from the first two X-ray observations during 06:03-17:04 UTC on 2006 February 24, revealed strong QPOs at $\sim 8.5$ Hz (Homan, Miller and Wijnands 2006). Third observation (13:20-13:43 UTC) on the same day showed only a weak QPO at around 6.4 Hz. The last 2 observations (14:55-17:04 UTC) again indicated the presence of strong QPOs at 5.0 Hz.

Rupen, Dhawan and Mioduszewski (2006a), detected with VLA a radio object in the error box of the X-ray source having a flux density of 2.1 mJy at 1.4 GHz on 2006 January 31. The radio source faded away by 2006 February 2 (Rupen, Dhawan and Mioduszewski 2006b). A bright optical counterpart of the X-ray source was found at the time of the outburst with $V = 11.3$ magnitude and its brightness decreased to $V = 15.5$ by February 10 (Torres et al. 2006). The optical star was also detected in the near-infrared with a $K$ magnitude of 15.0 on 2006 February 7 (D’Avanzo et al. 2006). Near-UV observations with the Optical Monitor on the XMM-Newton showed variations in the UV flux correlated to the hard X-ray flux variations (Sala et al. 2007).

All these characteristics strongly suggest that XTE J1817-330 is most likely a black hole binary. This transient was repeatedly observed with the Proportional Counter Array (PCA) on RXTE in the pointed mode during the period 2006 January 27 - August 2. We have carried out detailed timing analysis of the PCA data to study the properties of the QPOs and in this paper we present the results of this analysis.

### 2 OBSERVATIONS AND DATA REDUCTION

The data for our analysis are taken from the HEASARC data archive [http://heasarc.gsfc.nasa.gov/]. We have used data acquired from the observations obtained during 2006, January 27 - August 2 with the 160 PCA pointing’s. The PCA consists of five xenon proportional counter units (PCUs) sensitive in 2-60 keV energy range with a total effective area of $\sim 6500$ cm$^2$ at $\sim 10$ keV (Jahoda et al. 1996). We used data from only the PCU2 for generating the light curves, energy spectra and the hardness ratio of the source as this unit was operating in all the observations.

FTOOLS version 6.1 was employed for the analysis and the calibration data files of epoch 3 and 4 were used for the energy response matrix. The XTE filter file is created using task xtefilt in FTOOLS with a time step of 16 second. The binned mode data were reduced to create the light curve files for all the observation Id’s using saexctr with a bin size of 7.8125 milli second. Event mode data were used for constructing the power density spectra (PDS) in the 15-25 keV energy range. These data were extracted from the
light curve files using the same binning time as used for the binned mode data using seectr task in FTOOLS. The spectral studies of XTE J1817-330 were carried out by using standard 2 mode data for the PCU 2 with a binning time of 16 sec.

3 DATA ANALYSIS AND RESULTS

The X-ray light curve of the transient was constructed by using the 1.5-12 keV count rates from the ASM and it is shown in Fig[1]. In the ASM light curve the source reached a peak intensity of about 1.9 Crab on 2006 January 28 and then declined with an e-folding time of about 27 days. There is indication of a broad peak between 2006 January 28 to 2006 February 2. After a lapse of about 120 days since the peak intensity, the source became undetectable. Similar light curves were obtained by Rykoff et al. (2007) and Sala et al. (2007) using the ASM daily average count rates for the entire duration of the outburst. Sala et al. (2007) also derived variation of the hardness ratios using the count rates in 3.0-5.0 keV / 1.5-3.0 keV and 5.0-12 keV / 3.0-5.0 keV using the ASM data from 2006 January 30 to April 30. We have computed the hardness ratio [(6-13) keV counts / (2-6) keV counts] from the PCA 2 data and this is shown as a function of the source intensity in Fig[2]. We used the spectral state classification of Gierlinski, Done and Page (2008) to indicate the spectral state of the source in Figures 1 and 2. From MJD 53764 (2006 January 29) the source was in HS state for 70 days with a hardness ratio less then 0.2. The source then moved to the US state characterized by a very low hardness ratio (< 0.1), and again appeared to move back to HS state. After 120 days of the HS state, the source, passed through 15 days of intermediate state with hardness ratio in the range 0.2-0.4. Finally it reached the LH state with a hardness ratio > 0.4. Gierlinski, Page, and Done (2008) had also presented a similar plot (Figure 2) of hardness ratio obtained from 6.3-10.5 keV count rates / 3.8-6.3 count rates using the PCA (RXTE) data. There is close resemblance between the two sets of curves even though the energy bands are different.

3.1 QPO Analysis and Results

The PDS is a powerful method for probing the rapid variability in the black hole and other accretion powered X-ray binaries. The PDS of many BHBs exhibits narrow and broad QPOs peaks whose width and position vary with time. A search for the QPOs in XTE J1817-330 was carried out in 2-8 keV, 8-14 keV and 15-25 keV bands. The power density spectra were constructed for all the observations using powspec. All the power spectra were normalized such that their integral gives the squared rms fractional variability (therefore the power spectrum is in units of (rms)^2/Hz) with the expected white noise level subtracted. The binned mode data were used for the 2-8 keV and 8-14 keV bands and the event mode data were used for the 15-25 keV for generating the PDS. The power law and the Lorentzian models have been used for fitting the QPO profiles. A QPO feature is detected in the 2-8 keV band in 10 of the observations. The observations showing presence of the QPOs are indicated by vertical arrows in the ASM light curve in Fig[1]. It may be noted that the QPOs are detected only when the source was bright (40-150 ASM counts sec^{-1}). As the source intensity declined to a level below 40 ASM counts sec^{-1}, the QPOs disappeared. The QPO occurrence is also indicated in the plot of hardness ratio versus source intensity in Fig[2] by star symbol. In 6 of these 10 observations, the QPOs are present in the 8-14 keV energy band. At the higher energy (15-25 keV), the QPOs are detected only in 5 of the observations.

The power density spectra in the different energy ranges for three of the observations are shown in Figures 3-5. Prominent QPO peaks are present in the PDS. The QPO feature at ≈ 5 Hz is detected prominently in the higher energy band (15-25 keV). A first harmonic of the fundamental QPOs at ≈ 10 Hz is also present in the PDS. Note that the first harmonic is quite prominent in the 2-8 keV (Fig[3a]) and the peak at ≈ 10 Hz in Fig[3b] for 8-14 keV band is even stronger then the peak at ≈ 5 Hz. The fundamental QPO peaks appear at about the same frequency in the plots in the three different energy bands. The power density spectra for MJD 53790.2 are shown in Fig[4]. There is no indication of the presence of QPOs in 2-8 keV but a broad QPO peak is clearly seen at about 9 Hz in the PDS of 8-14 keV. It is conceivable that the 5 Hz peak is blended in the rather broad 9 Hz peak. Note that if the 9 Hz peak is identified as the first harmonic as seen in Figs 3, 4 and 5, the peak due to fundamental QPO frequency at ≈ 5 Hz is undetectable in Fig 6(a) and (b). Small but insignificant peaks can be seen in Fig[4] at ∼ 3 Hz in 2-8 keV and 8-14 keV bands and at ∼ 3 Hz and ∼ 0.8 Hz in 8-14 keV and 15-25 keV bands in Fig[5].

A summary of the characteristic of the QPOs eg., frequency, amplitude and width for all the observations that showed the presence of the QPOs, is presented in Table 3. It may be noticed from the table that the data of MJD 53790.2 and 53790.3, show no detectable QPOs in 2-8 keV. However the QPOs are clearly present in the 8-14 keV at a higher frequency of ≈ 8-9 Hz. The QPO peaks in the 8-14 and 15-25 keV bands are rather broad with δν in 1.8 to 3 Hz range. This is unlike the QPOs detected in the other observations where the peaks are narrow with δν less then 1 Hz. Consequently the Q values are rather low being 3 to 4. The values of the coherence parameter (quality factor, Q=ν/δν) are all greater than 2.

We found no correlation in the amplitude of fundamental QPO and amplitude of first harmonics. The QPO amplitudes were not found to show any correlation with the overall source intensity or hardness ratio. No trend was observed between the QPO amplitudes derived in the two energy bands 2-8 keV and 8-14 keV. Similarly no correlation was detected in the variation of power-law flux with QPO fundamental frequency and rms amplitude of the QPOs. We found from the PDS studies on 2006 February 24 that the QPOs were present in high/soft state of the source with spectral power-law index varying in the range 2.1-2.3. Our result are supported by the findings of Homan et al. (2006) who discovered rapid variability in the QPO properties on the same day. The QPOs were observed in high/soft...
3.2 Spectral Analysis and Results

We have analyzed the spectral data from the RXTE for those observations in which the QPOs are detected. For a comparison the spectra are also obtained for a few observations in which no QPOs are detected to investigate whether there are any differences in the spectral parameters. Background subtracted standard 2 mode data from the PCU 2 with 16 sec binning were used to construct the spectra. The energy spectra of selected observations were fitted with a power law model taken from XSPEC version 12 for high energy component of the spectrum, plus a standard disk black body, diskbb model (accretion disk consisting of multiple blackbody components) taken from XSPEC (Mitsuda et al. 1984 ; Makishima et al. 1986). It also included the photoelectric absorption (wabs) model from (Morrison and McCammon, 1983) and the Xenon edge at \(\approx 4.7 \text{ keV}\) to account for the PCA response and is not intrinsic part of the spectrum. In the spectrum of MJD 53768 a Gaussian line model is also added to account for the presence of an iron line at 6.4 keV. In the spectral fits a fixed value of hydrogen column density \((N_H) = 1.2 \times 10^{21} \text{ cm}^{-2}\) has been used (Rykoff et al. 2007).

The analyzed epochs included (a) MJD 53768, 53789, 53790 and 53790.6 that show presence of the QPOs in the entire 2-25 keV energy region, (b) MJD 53790.2 and 53790.3 in which broad QPO peaks in the 8-14 keV band are present but not in the 2-8 keV interval (c) MJD 53778, 53780, 53786 and 53790.5 data with the QPO detection only in the 2-8 keV band but not at > 8 keV (d) MJD 53766 and 53791 data with the QPOs in the 2-14 keV interval but not at > 15 keV (e) MJD 53764 and 53775 when no QPOs are detected (f) MJD 53794 and 53797 when the QPOs have declined and the QPOs are not present. In Table 2 we have compiled the derived values of the temperature \((T_{\text{in}})\) of the disk black body component, photon spectral index \((\alpha)\) of the hard component as well as the flux values of the thermal, and the power law components. Ratio of the power law flux to the thermal flux is also computed and shown in Table 2. Following points are to be noted from the table: (I) As expected for the black hole binaries the thermal component is dominant in the initial part of the outburst lasting for about first 25 days. This is obvious from the values of flux ratio that lies in 0.06 to 0.27 range. (II) After 1/\(e\) decay of the intensity, the thermal component declined substantially and the thermal and the power law fluxes became comparable. (III) When the intensity declined further (after MJD 53791) the power law flux declines and the thermal flux dominates. Note that the power law spectral index lies in a narrow region of 2.1-2.3 for all the observations selected for the spectral studies. These values are comparable within the errors of the photon index values estimated by Gierlinski, Done and Page (2008) for some of the observations. The temperature of the disk is \(\approx 1 \text{ keV}\) and constant during the first 30 days but there is indication of cooling of the disk as shown by \(kT \approx 0.8\) with further decline of the intensity in the last two observations. A few representative energy spectra are shown in Fig 5. The systematic errors for all the fits are within 3%.

4 DISCUSSION

The LFQPOs occur most frequently when the power law flux is the dominating component in the energy spectrum. Some times they are also present in the high luminosity state with the presence of a hard component. From table 1 and 2 it will be noticed that in all the cases of the detection of LFQPOs from XTE J1817-330, except the observations of MJD 53764 and 53775 in which no QPOs are detected, the ratio of the power law flux to the thermal disk flux lies in 0.20 to 1.13 range consistent with its occurrence only in the states with a significant power law component. Also note that the LFQPOs have significant coherence \((Q = \nu/\delta \nu)\) with the Q in range of 3-11 and their rms amplitude vary from a few percent to as high as 13%.

Variation of the QPO frequency with the source intensity is another feature detected in some BHBs. The fundamental QPO frequency in XTE J1817-330 varies in a narrow band of 4.4-5.9 Hz. We have investigated the variation of the QPO frequency in the 2-8 keV band with the thermal disk component flux \((d_{\text{bb}})\). This is shown in Fig 6 and a trend similar to that of Fig 7(a) is seen here indicating that the frequency is correlated with the thermal disk component. As expected a clear 1:2 relationship of the QPO fundamental frequency and that of the first harmonic is seen.

All the characteristics of the LFQPOs reported by us in this paper from XTE J1817-330 are similar to those seen in the other black hole binaries and further strengthen the black hole nature of this source (Remillard et al. 2003).

Correlation of the properties of LFQPOs with the spectral parameters of the BHBs has been studied in detail for several sources (Muno, Remillard and Morgan 2001; Tomsick and Kaaret 2001; Remillard et al. 2003; Belloni, Psaltis and van der Klis 2002; Vignarca et al. 2003; Rossi, Homan and Belloni 2004). These studies show that the LFQPO characteristics are generally well correlated with the thermal disk and the power law components of the energy spectra. While the QPO frequency is closely correlated with the disk flux, the amplitude of the QPOs for the fundamental frequency is found to track the flux
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We have detected the QPOs in the 8-14 keV band but not in the 2-8 keV for the observations of MJD 53790.2 and 53790.3. This is similar to the detection of the QPOs at the high energy and its absence at the low energy in some observations from GRS 1915+105 (Chakrabarti and Manickam 2000). This behavior of GRS 1915+105 was explained by Chakrabarti and Manickam (2000) on the basis of “on” and “off” (burst and quiescent) state of the source with the shock oscillation model. Further detailed studies of the LFQPOs at the higher energy are required to test the validity of the model.

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REFERENCES

Belloni T., Psaltis D., van der Klis M., 2002, ApJ, 572, 392

Chakrabarti & Manickam, 2000, ApJ, 531, L41

D’Avanzo P., Goldoni P., Covino S., Campana S., Molinari E., Chincarini G., Zerbi F. M., Testa V., Tosti G., Vitali F., 2006, ATel 724

Gierlinski M., Done C., Page K., 2008, MNRAS, 388, 753

Homan J., Miller J. M., Wijnands R., 2006, ATel 752

Jahoda K., Swank J. H., Giles, A. B., Stark M. J., Strohmayer T. E., Zhang W., Morgan, E. H., 1996, SPIE, 2808, 59

Kuulkers E., Goldoni P., Shaw S. E., Brandt S., Chenevez J., Courvoisier T. J. L., Ebisawa K., Kretschmar P., Markwardt C., Mowllavi N., 2006, ATel 738

Lehr D. E., Wagoner R.V., Wilms J., 2000, astro-ph 0004211v1

Levine A. M., Bradt H., CUI W., Jernigan J. G., Morgan E.J., Remillard R.A., Shirley R. E., Smith D. A., 1996,
ApJ, 469, L33

Makishima K., Maejima Y., Mitsuda K., Bradt H. V., Remillard R.A., Tuohy I. R., Hoshi R., Nakagawa M., 1986, ApJ, 308, 635

McClintock, J.E., Remillard, R.A., 2006, in Lewin, W.H.G., van der Klis, M. (Eds.), Compact Stellar X-ray Sources, Cambridge University Press, Cambridge, 157

Miller J. M., Homan J., Steeghs D., Torres M. A. P., Wijnands R., 2006a, ATel 743

Miller J. M., Homan J., Steeghs D., Wijnands R., 2006b, ATel 746

Mitsuda K., Inque H., Koyama K., Makishima K., Matsuoka M., Ogawara Y., Shibazaki N., Suzuki K., Tanaka Y., Hirano H., 1984, PASJ, 36, 741

Morrison R., McCammon D., 1983, ApJ, 270, 119

Morgan E. H., Remillard R. A., 1997, ApJ, 482, 993

Muno M., Remillard R., Morgan E., 2001, ApJ, 556, 515

Remillard R.A., Muno M.P, McClintock J.E., Orosz J., 2003, in Proc. Fourth Microquasar Workshop: New Views on Microquasars, ed. P. Durouchoux Y. Fuchs, & J. Rodriguez (Kolkata: Center for Space Physics), 57

Remillard R.A., McClintock J.E., 2006a, ARAA, 44, 49

Remillard R.A., Levine A. M., Morgan E. H., Markwardt C. B., Swank J. H., 2006b, ATel 714

Rossi S., Homan J., Belloni T., 2004, Nuclear Physics B (Proc. Suppl.), 132, 1416

Rupen M. P., Dhawan V., Mioduszewski A. J., 2006a, ATel 717

Rupen M. P., Dhawan V., Mioduszewski, A. J., 2006b, ATel 721

Rykoff E. S., Miller J. M., Steeghs D., Torres M. A. P, 2007, ApJ, 666, 1129

Sala G., Greiner J., Ajello M., Bottacini E., Haberl F., 2007, A & A, 473, 561

Shaw S. E., Zurita J., Kuulkers E., Brandt S., Chenevez J., Courvoisier T. J.L., Ebisawa K., Kretschmar P., Markwardt C., Mowlavi N., 2006, ATel 731

Tomsick & Kaaret, 2001, ApJ, 548, 401

Torres M. A. P., Steeghs D., Jonker P. G., Luhman K., McClintock J. E., Garcia M. R, 2006, ATel 733

Trudolyubov S, Churazov E., Gilfanov M., 1999, Astron. Lett., 25, 718
Table 1. Summary of the characteristics of the QPO in the three energy bands. MJD 53766 corresponds to the date 2006-01-31.

| MJD       | Duration Of Observation (sec) | Energy Range (keV) | Power Law Index | Frequency (Hz) | Width (Hz) | Quality Factor | RMS % | Frequency (Hz) | Width (Hz) | Quality Factor | RMS % | First Harmonic | Reduced Chi Sq† |
|-----------|-------------------------------|--------------------|-----------------|---------------|------------|----------------|-------|---------------|------------|----------------|-------|----------------|-----------------|
| 53766(Q1) | 3947                          | 2-8                | -1.25           | 5.43±0.04     | 0.83±0.09   | 6.7            | 2.5   | 10.82±0.50    | 1.49±0.85   | 7.6            | 0.9  | 1.7            |                  |
|           |                               | 8-14               | -0.56           | 5.42±0.03     | 0.67±0.06   | 8.7            | 3.9   | 10.86±0.50    | 2.62±1.99   | 4.2            | 6.8  | 0.9            |                  |
| 53768(Q2) | 5274                          | 2-8                | -1.28           | 5.39±0.02     | 0.89±0.07   | 6.0            | 2.6   | 10.93±0.15    | 1.19±0.36   | 9.2            | 1.0  | 2.4            |                  |
|           |                               | 8-14               | -0.57           | 5.55±0.13     | 0.74±0.33   | 7.4            | 3.2   | 10.89±0.10    | 2.15±0.28   | 5.1            | 7.4  | 1.0            |                  |
|           |                               | 15-25              | -0.32           | 5.14±0.19     | 0.64±0.58   | 8.1            | 3.9   | 10.83±0.26    | 2.22±0.70   | 4.9            | 8.1  | 1.0            |                  |
| 53778(Q3) | 10329                         | 2-8                | -1.19           | 4.41±0.14     | 1.14±0.34   | 3.9            | 2.0   | 7.84±0.06     | 0.30±1.19   | 26.1           | 1.0  | 1.7            |                  |
| 53780(Q4) | 13549                         | 2-8                | -1.09           | 4.80±0.09     | 0.79±0.24   | 6.1            | 2.2   | 9.83±0.24     | 0.91±0.62   | 10.8           | 1.3  | 1.2            |                  |
|           |                               | 8-14               | -1.25           | 5.12±0.08     | 1.16±0.17   | 4.7            | 2.5   | 10.35±0.54    | 1.82±0.85   | 5.7            | 1.4  | 1.6            |                  |
|           |                               | 2-8                | -1.87           | 5.05±0.10     | 1.34±0.21   | 3.8            | 2.5   | 10.66±0.31    | 0.67±0.97   | 15.8           | 1.0  | 1.5            |                  |
| 53786(Q5) | 8413                          | 2-8                | -0.38           | 5.29±0.12     | 0.82±0.33   | 6.2            | 2.5   | -             | -         | -              | -    | -              |                  |
|           |                               | 8-14               | -1.11           | 5.27±0.11     | 1.54±0.31   | 3.5            | 2.4   | 10.78±0.24    | 1.42±0.51   | 7.6            | 1.4  | 1.4            |                  |
| 53789(Q6) | 2769                          | 2-8                | -1.09           | 5.57±0.03     | 0.94±0.05   | 5.9            | 7.0   | 10.18±0.32    | 2.92±0.74   | 3.5            | 2.4  | 1.5            |                  |
|           |                               | 8-14               | -2.42           | 5.57±0.03     | 0.95±0.07   | 5.9            | 13.2  | 10.56±0.45    | 2.94±0.94   | 3.6            | 5.2  | 1.2            |                  |
|           |                               | 15-25              | -1.82           | 5.50±0.07     | 1.01±0.13   | 5.6            | 11.5  | 10.97±2.10    | 2.96±2.33   | 3.7            | 4.5  | 0.9            |                  |
| 53790(Q7) | 4132                          | 2-8                | -1.43           | 5.61±0.03     | 1.06±0.07   | 5.2            | 6.7   | 10.68±0.53    | 1.89±1.06   | 5.7            | 2.0  | 1.6            |                  |
|           |                               | 8-14               | -2.48           | 5.60±0.14     | 1.00±0.11   | 5.3            | 12.3  | 12.34±1.53    | 5.27±2.67   | 2.3            | 6.0  | 0.9            |                  |
|           |                               | 15-25              | -2.11           | 5.54±0.13     | 1.33±0.29   | 4.0            | 12.0  | -             | -         | -              | -    | -              |                  |
| 53790.2(Q8)| 3179                         | 2-8                | -1.09           | NO QPO        | -           | -              | -     | -             | -         | -              | -    | -              |                  |
|           |                               | 8-14               | -9.06±0.32     | 2.99±1.37     | 3.0          | 8.8            | -     | -             | -         | -              | -    | -              |                  |
| 53790.3(Q9)| 1967                         | 2-8                | -1.12           | NO QPO        | -           | -              | -     | -             | -         | -              | -    | -              |                  |
|           |                               | 8-14               | -7.83±0.16     | 2.03±0.68     | 3.8          | 9.4            | -     | -             | -         | -              | -    | -              |                  |
|           |                               | 15-25              | -7.97±0.35     | 1.78±1.28     | 4.5          | 9.6            | -     | -             | -         | -              | -    | -              |                  |
| 53790.5(Q10)| 3024                        | 2-8                | -0.82           | 5.88±0.35     | 1.91±0.77   | 3.1            | 1.7   | -             | -         | -              | -    | -              |                  |
| 53790.6(Q11)| 3686                        | 2-8                | -1.16           | 4.87±0.02     | 0.44±0.04   | 11.0           | 5.7   | 9.60±0.22     | 1.20±0.54   | 8.0            | 1.9  | 1.6            |                  |
|           |                               | 8-14               | -1.29           | 4.85±0.02     | 0.44±0.05   | 11.1           | 12.9  | 9.44±0.35    | 0.43±2.23   | 22.1           | 2.3  | 1.0            |                  |
|           |                               | 15-25              | -0.42           | 4.91±0.09     | 0.55±0.13   | 9.0            | 12.6  | -             | -         | -              | -    | -              |                  |
| 53791(Q12)| 3564                          | 2-8                | -1.34           | 5.03±0.02     | 0.58±0.03   | 8.8            | 6.4   | 9.86±0.11     | 1.26±0.20   | 7.8            | 2.4  | 1.6            |                  |
|           |                               | 8-14               | -2.16           | 5.01±0.02     | 0.59±0.04   | 8.5            | 13.3  | 9.73±0.27    | 1.89±0.72   | 5.2            | 4.9  | 1.7            |                  |

†: Reduced chi square refer to the goodness of fit of the entire spectrum.
Table 2. Summary of the spectral fit parameter for the selected observations of XTE J1817-330. MJD 53764 corresponds to the date 2006-01-29.

| MJD      | DURATION OF OBSERVATION (sec) | Photon Index | Normalization | Flux (ergs/cm\(^2\)/s) \(10^{-8}\) | Tin (keV) | Normalization \(\times 10^3\) | Flux (ergs/cm\(^2\)/s) \(10^{-8}\) | Reduced Chi Square | Energy Range (keV) | Total Flux 3-25 keV (ergs/cm\(^2\)/s \(10^{-8}\)) | Flux Ratio(1) |
|----------|-------------------------------|--------------|---------------|-------------------------------------|-----------|-------------------------------|-------------------------------------|-------------------|-----------------|-----------------------------------------------|--------------|
| 53764    | 3117                          | 2.17(±0.24)  | 0.54(±0.34)   | 0.12                                | 0.99(±0.01)| 3.13(±0.41)                   | 1.59                                | 0.6               | 3-15            | 1.72                                                          | 0.08         |
| 53766(Q1)| 3947                          | 2.31(±0.04)  | 2.63(±0.34)   | 0.45                                | 1.04(±0.01)| 2.52(±0.14)                   | 1.71                                | 1.1               | 3-20            | 2.16                                                          | 0.27         |
| 53768(Q2)| 5274                          | 2.34(±0.04)  | 2.57(±0.34)   | 0.42                                | 1.03(±0.01)| 2.45(±0.21)                   | 1.58                                | 1.9               | 3-25            | 2.01                                                          | 0.27         |
| 53775    | 3958                          | 2.09(±0.27)  | 0.25(±0.19)   | 0.07                                | 0.95(±0.007)| 2.94(±0.12)                   | 1.21                                | 1.2               | 3-20            | 1.27                                                          | 0.06         |
| 53778(Q3)| 10329                         | 2.08(±0.06)  | 0.68(±0.18)   | 0.19                                | 0.95(±0.01)| 2.45(±0.21)                   | 0.95                                | 1.1               | 3-20            | 1.14                                                          | 0.20         |
| 53780(Q4)| 13549                         | 2.06(±0.06)  | 0.61(±0.12)   | 0.18                                | 0.94(±0.01)| 2.29(±0.18)                   | 0.85                                | 1.2               | 3-18            | 1.03                                                          | 0.21         |
| 53786(Q5)| 8413                          | 2.03(±0.06)  | 0.48(±0.08)   | 0.15                                | 0.91(±0.01)| 2.01(±0.16)                   | 0.63                                | 1.3               | 3-18            | 0.79                                                          | 0.24         |
| 53789(Q6)| 2769                          | 2.27(±0.03)  | 2.79(±0.27)   | 0.51                                | 1.05(±0.02)| 0.73(±0.87)                   | 0.53                                | 1.4               | 3-25            | 1.05                                                          | 0.97         |
| 53790(Q7)| 4132                          | 2.26(±0.03)  | 2.74(±0.24)   | 0.51                                | 1.05(±0.02)| 0.72(±0.88)                   | 0.51                                | 1.8               | 3-25            | 1.02                                                          | 1.01         |
| 53790.2(Q8)| 3179                        | 2.13(±0.05)  | 1.80(±0.26)   | 0.44                                | 1.07(±0.02)| 0.59(±0.74)                   | 0.45                                | 1.2               | 3-20            | 0.89                                                          | 0.99         |
| 53790.3(Q9)| 1967                        | 2.15(±0.03)  | 2.01(±0.21)   | 0.47                                | 1.07(±0.02)| 0.53(±0.70)                   | 0.42                                | 1.3               | 3-25            | 0.89                                                          | 1.13         |
| 53790.5(Q10)| 3024                       | 2.17(±0.04)  | 1.58(±0.20)   | 0.35                                | 1.00(±0.02)| 0.94(±0.13)                   | 0.54                                | 1.5               | 3-25            | 0.89                                                          | 0.65         |
| 53790.6(Q11)| 3686                        | 2.26(±0.04)  | 2.10(±0.27)   | 0.39                                | 1.03(±0.02)| 1.03(±0.89)                   | 0.52                                | 1.3               | 3-20            | 0.91                                                          | 0.75         |
| 53791(Q12)| 3564                          | 2.22(±0.05)  | 2.08(±0.29)   | 0.42                                | 1.04(±0.02)| 0.81(±0.93)                   | 0.53                                | 1.2               | 3-20            | 0.95                                                          | 0.80         |
| 53794    | 3345                          | 2.08(±0.12)  | 0.29(±0.09)   | 0.07                                | 0.84(±0.01)| 2.14(±0.21)                   | 0.39                                | 1.1               | 3-15            | 0.47                                                          | 0.20         |
| 53797    | 5539                          | 2.26(±0.10)  | 0.39(±0.10)   | 0.07                                | 0.82(±0.01)| 2.31(±0.18)                   | 0.35                                | 1.6               | 3-15            | 0.42                                                          | 0.21         |

(1): Ratio of power law flux to diskbb flux
Figure 1. The ASM lightcurve in the 1.5-12 keV range is shown in panel (a) from 2006-Jan-29 (MJD 53764) to 2006-Aug-02 (MJD 53950). The count rates are averaged over a day. The position of the observed QPOs are indicated by the vertical arrows. The PCA lightcurves in the 2-6 keV and 6-13 keV energy bands are shown in (b) and (c). The corresponding hardness ratio obtained from counts in 6-13 keV / 2-6 keV is shown in panel (d) for the 100 pointed PCA observations.
Figure 2. Variation of the Hardness Ratio (counts in (6-13) keV / counts in (2-6) keV) with the count rate (s$^{-1}$) in (2-13) keV from only PCU 2, is shown during the 2006 outburst of the source. Filled $\ast$ symbols represent the positions where the QPOs are detected.
Figure 3. Power density spectra for the observation of MJD 53768. The PDS is shown for 2-8 keV in panel (a), 8-14 keV in panel (b) and 15-25 keV in panel (c). Arrows in the panels (a), (b) and (c) indicate the fundamental frequencies of the QPOs at 5.39 Hz, 5.55 Hz and 5.14 Hz. The first harmonic at ≈ 10 Hz is more prominent than the fundamental frequency peak in panel (b) and (c).
Figure 4. Power density spectra for the observations of MJD 53789. The PDS is shown for 2-8 keV in panel (a), 8-14 keV in panel (b) and 15-25 keV in panel (c). Arrows in the panels indicate the fundamental frequencies of the QPOs at 5.57 Hz, 5.57 Hz and 5.5 Hz. The first harmonic at \( \approx 10 \) Hz is weaker compared to the fundamental frequency at \( \approx 5 \) Hz in all the panels.
Figure 5. Power density spectra for observation of MJD 53790. The PDS is shown for 2-8 keV in panel (a), 8-14 keV in panel (b) and 15-25 keV in panel (c). Arrows in the panel (a), (b) and (c) indicate the fundamental frequencies of QPOs at 5.61 Hz, 5.60 Hz and 5.54 Hz.
Figure 6. Power density spectrum for the MJD 53790.2 is shown in panel (a) for 2-8 keV, and (b) for 8-14 keV energy band. The arrow indicate the position of broad QPO at 9.06 Hz in panel (b). The QPOs are not detectable in (2-8) keV but a broad and asymmetric peak is present in panel (b) at about 9 Hz.
Figure 7. Plots of the QPO frequency versus the source intensity are shown in the three energy bands. These are background subtracted source count rates (counts s$^{-1}$) taken only from PCU 2 in the energy intervals (a) 2-8 keV, (b) 8-14 keV and (c) 15-25 keV.
Figure 8. Some representative energy spectra with the unfolded models are shown in this figure. For details of the spectral model refer to page 5. Thick black lines indicates the total spectrum that is a sum of all the components. Symbol "D" denotes the disk black body component of the models used to fit the spectra, "P" indicates the power law component and gaussian line model is denoted by symbol "G". Fig (a) shows spectrum in the 3-25 keV for MJD 53768, (b) for MJD 53789 and (c) for MJD 53790 in which the QPOs are detected in the entire 3-25 keV energy range. Panel (d) shows spectrum in the 3-15 keV for MJD 53794 in which no QPO is detected.
Figure 9. Variations of the QPO fundamental frequency in the 2-8 keV band (open circle) and first harmonics frequency (filled stars) with the flux of the disk black body component is shown for XTE J1817-330 during its 2006 outburst.