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## Discovery of a neutron star with spin frequency 530 Hz in A1744-361

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### ABSTRACT

We report the detection with the Rossi X-ray Timing Explorer (RXTE) Proportional Counter Array (PCA) of 530 Hz burst oscillations in a thermonuclear (Type I) burst from the transient X-ray source A1744-361. This is only the second burst ever observed from this source, and the first to be seen in any detail. Our results confirm that A1744-361 is a low mass X-ray binary (LMXB) system harboring a rapidly rotating neutron star. The oscillations are first detected along the rising edge of the burst, and show evidence for frequency evolution of a magnitude similar to that seen in other burst sources. The modulation amplitude and its increase with photon energy are also typical of burst oscillations. The lack of any strong indication of photospheric radius expansion during the burst suggests a 9 kpc upper limit of the source distance. We also find energy dependent dips, establishing A1744-361 as a high inclination, dipping LMXB. The timescale between the two episodes of observed dips suggests an orbital period of  $\sim 97$  min. We have also detected a 2 - 4 Hz quasi-periodic-oscillation (QPO) for the first time from this source. This QPO appears consistent with  $\sim 1$  Hz QPOs seen from other high inclination systems. We searched for kilohertz QPOs, and found a suggestive  $2.3\sigma$  feature at 800 Hz in one observation. The frequency, strength and quality factor are consistent with that of a lower frequency kilohertz QPO, but the relatively low significance argues for caution, so we consider this a tentative detection requiring confirmation.

*Subject headings:* equation of state — stars: neutron — stars: rotation — X-rays: binaries — X-rays: bursts — X-rays: individual (A1744-361)

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## 1. Introduction

The X-ray transient A1744-361 was discovered by Ariel V in 1976, when the source was in outburst (Davison et al. 1976; Carpenter et al. 1977). No optical counterpart was identified (Burnell & Chiappetti 1984), and no thermonuclear (type I) X-ray bursts were reported. The source was observed to be in outburst again 13.5 years later in August 1989 (in't Zand 1992; in 't Zand 2004). This time it was detected by COMIS-TTM, and the source was at a relatively constant level of  $\sim 60$  mCrab (about three times fainter than in 1976; see in't Zand 1992). It was at least 10 times weaker (and undetectable) five months earlier and one month later (in 't Zand 2004). The source spectrum was indicative of a soft transient (in't Zand 1992). Emelyanov et al. (2001) analysed data from COMIS-TTM and found 33 likely type I bursts from several X-ray sources in the field containing A1744-361. They found a burst from the Aug 23, 1989 data from A1744-361. The burst was detected with 8 s time resolution, by comparison of the source flux during the likely burst and the session-averaged source flux. No burst profile or detailed information about this burst was given. Moreover, Emelyanov et al. (2001) made a classification of the observed bursts as type I (thermonuclear) based only on their identification with known classical bursters, while at the time A1744-361 was not known to be a burster. However, they considered this burst to be the first detection of a type I X-ray burst from this source, and suggested that A1744-361 contains an accreting neutron star.

Since 2003, A1744-361 has been in outburst every year, detected by RXTE (ASM and PCA), Chandra, and INTEGRAL (Remillard et al. 2003; McClintock et al. 2003; Torres et al. 2004; Markwardt & Swank 2004; Grebenev et al. 2004; Swank & Markwardt 2005). The detections of radio and optical counterparts of this source have also been reported (Rupen et al. 2003; Steeghs et al. 2004). However, these detections (in 2003 & 2004) did not show any type I X-ray bursts.

Discovery of type I bursts from an X-ray source can conclusively classify it, as these bursts are produced by thermonuclear burning of matter accumulated on the surfaces of accreting neutron stars (Joss 1977; Lamb, & Lamb 1978). Moreover, thermonuclear bursts are observed only from LMXBs (Strohmayer & Bildsten 2003; Liu, van Paradijs, & van den Heuvel 2001). By analysing 2005 RXTE PCA data, we have found a type I burst from this source, which confirms the earlier conclusion of Emelyanov et al (2001).

We have also discovered millisecond period brightness oscillations with a frequency of  $\approx 530$  Hz during this burst. These oscillations are produced by an asymmetric brightness pattern on the stellar surface that is modulated by rotation of the star (Chakrabarty et al. 2003; Strohmayer & Bildsten 2003). Therefore, the burst oscillation frequency is identical to, or very close to the stellar spin frequency. Hence, our detection of  $\sim 530$  Hz burst oscillations

establishes the spin frequency of the neutron star in A1744–361.

Analysing the 2003 RXTE PCA data, we have discovered two episodes of energy dependent dips in the X-ray flux from A1744. The time interval between the two sets of dips in two successive RXTE orbits indicates that the orbital period of A1744–361 is  $97 \pm 22$  min. We also report the discovery of a low frequency quasi-periodic-oscillation (QPO;  $\sim 3$  Hz), as well as an indication of a lower kHz QPO ( $\sim 800$  Hz) from this source. In § 2, we describe the analysis of the data, and present our results. In § 3, we discuss the implications of our findings.

## 2. Data Analysis and Results

We analysed RXTE PCA data from the transient source A1744–361 when it was in outburst in 2003, 2004, and 2005. In  $\sim 55$  ks of data, we found a single thermonuclear X-ray burst (July 16, 2005). The rise time of the burst is  $\sim 1$  s, while the decay time is  $\gtrsim 10$  s (see Fig. 1). The peak count rate of the burst was  $\gtrsim 6000$  with 3 PCUs operating. We created burst profiles for different energy ranges, and also hardness profiles for several pairs of energy ranges. We also performed a time resolved spectral analysis by fitting blackbody spectra through the burst. The lack of any significant drop in the blackbody temperature correlated with an increase in the blackbody normalization (ie. radius), leads us to conclude that this is not a photospheric radius expansion (PRE) burst. The burst had a peak flux in the 2 - 20 keV band of  $1.9 \times 10^{-8}$  ergs  $\text{cm}^{-2}$   $\text{s}^{-1}$ . Considering this flux to be less than the Eddington flux, the upper limit to the source distance is  $\approx 9$  kpc, for a  $1.4 M_{\odot}$  neutron star mass, ionized hydrogenic accreted matter, and isotropic emission from the star.

In order to search for oscillations during the burst, we calculated power spectra with a Nyquist frequency of 2048 Hz for 4 s intervals starting from the burst onset, using 125  $\mu\text{s}$  event mode data. We found a candidate peak at  $\sim 530$  Hz in the first such spectrum. The main panel of Fig. 1 shows the 2 - 60 keV burst profile and the 4 s interval used to compute the power spectrum. The peak was resolved, so lowering the frequency resolution by averaging adjacent fourier bins improved the signal to noise ratio. At 2 Hz resolution we found a peak power of 10.3. The inset panel of Fig. 1 shows the 2 Hz resolution power spectrum. The probability of obtaining a power this high in a single trial from the expected  $\chi^2$  noise distribution (16 dof) is  $\approx 6.13 \times 10^{-11}$ . Multiplying by a conservative trials penalty of 8192, the number of frequency bins in the original spectrum, we arrive at a significance of  $5.02 \times 10^{-7}$ , which indicates a strong detection.

To get a rough idea about possible frequency evolution, we next calculated a dynamic

$Z^2$  power spectrum (Strohmayer & Markwardt 1999). We used 1 s intervals to compute  $Z^2$  power spectra, and started a new interval every 1/8 s. The corresponding power contours (see Fig. 2) are associated primarily with the rising portion of the burst profile, and the time evolution suggests that the oscillation frequency increases somewhat during the burst rise to peak. These properties are fairly typical of the behavior of oscillations seen in other burst sources, giving us even added confidence in the detection. The highest amplitude in the  $> 3$  keV band in a 1 s interval during the oscillation is 10.3 % (rms). The amplitude increases with energy, reaching 15% for photons above 8 keV. This behavior is also fairly typical of burst oscillations (Strohmayer et al. 1997; Muno, Ozel & Chakrabarty 2003). The pulse profile is sinusoidal, with no indications of significant harmonic structure.

We searched all the data for QPOs, and found a  $\sim 3$  Hz QPO in the April, 2004 data. We divided 750 s of data from the ObsId 90058-04-01-00 into  $M$  ( $= 75$ ) equal segments of 10 s duration, and calculated Fast Fourier Transforms on each time segment. In order to reduce the noise, the resulting power spectra were averaged, and  $W$  ( $= 8$ ) consecutive frequency bins were combined (making the frequency resolution 0.8 Hz). The upper figure of panel *a* of Fig. 3 shows this power spectrum, which clearly depicts a QPO of quality factor ( $Q$ )  $\sim 2$ , at  $\sim 3.5$  Hz (rms amplitude  $\sim 5\%$ ). For computing the significance of this QPO, we fitted the spectrum with a model, and minimized the corresponding  $\chi^2$  to get the best fit parameter values. Then we divided the power spectrum by the best fit model, and multiplied by 2 (see the upper figure of panel *b*, Fig. 3), in order to have the noise distributed as  $\chi^2$  with  $2MW$  degrees of freedom. The peak power (2.45) of the QPO, therefore, has the single trial significance of  $1.25 \times 10^{-7}$ . As low frequency QPOs are searched up to 100 Hz, multiplying by the number ( $= 125$ ) of trials, we get a significance of  $1.56 \times 10^{-5}$ , which implies a  $\sim 4.3\sigma$  detection. We also note that this QPO seems to shift by  $\sim 1$  Hz in  $\sim 40$  hours, as there is an indication of a  $\sim 2.5$  Hz QPO (with significance  $\sim 2.6\sigma$ , and rms amplitude  $\sim 3\%$ ; lower figures of panels *a* & *b* of Fig. 3) in the ObsId 90058-04-02-00 (Apr 10, 2004).

We searched for kHz QPOs in the whole data set, and found a tentative indication of a 800 Hz QPO in the ObsId 90058-04-02-00. The significance of this possible QPO is only  $\sim 2.3\sigma$ . However, its centroid frequency ( $\sim 800$  Hz) and high  $Q$ -value ( $\sim 62.5$ ) are consistent with those of lower kHz QPOs observed from other sources. The inferred amplitude (rms) of  $\sim 6\%$  is also consistent with lower frequency kHz QPOs in other sources.

We discovered intensity dips in the ObsId 80431-01-02-00 (Nov 17, 2003). The observed durations of the dips are between 5 s and 25 s. These dips appear only in the softer energy bands (see Fig. 4), which indicates that they are caused by partial obstruction of the central X-ray source by structures (above the equatorial plane) created within the accretion flow (White & Swank 1982; Jonker et al. 2000). We found two sets of dips in two subsequent

data segments. A particular set of dips may be caused by cold clouds (or other structures) distributed in a range of azimuthal angles above the accretion disk plane (see for example, Frank, King, & Lasota 1987). The time separation (97 min) between the two subsequent sets of dips gives an estimate of the orbital period of the binary system (White & Swank 1982). As the width of each set of dips introduces an uncertainty, we suggest that the orbital period of A1744–361 is  $97 \pm 22$  min. However, we note that the actual orbital period may be half (as we may have missed a set of dips because of the gap between two data segments), or twice this value (as secondary dips may occur in between two primary sets of dips; Smale et al. 1989).

### 3. Discussion and Conclusions

The X-ray transient A1744–361 has been an elusive source, observed only twice before 2003 (in 1976 and in 1989) with gaps of many years. As a result, detailed information about this source was lacking, except the strong indication (from an putative type I X-ray burst; Emelianov et al. 2001) that A1744–361 is a neutron star LMXB. Since 2003, the source has shown outbursts every year. Analysing 2005 RXTE PCA data, we found a thermonuclear burst from this source with certainty (as no other known candidate source was in the PCA field of view). We also discovered millisecond period brightness oscillations during this burst. From these results we confirm that this source is an LMXB harboring a neutron star. We infer the spin frequency of the neutron star to be  $\sim 530$  Hz from the burst oscillations. This value is consistent with the observed spin frequencies of the neutron stars in LMXBs, that range from 45 Hz to 619 Hz (Strohmayer & Bildsten 2003; Kaaret et al. 2005). More observations of bursts with oscillations from this source will be important, because the coherent addition of oscillation signals from several bursts may lead to a significant detection of harmonic power (Bhattacharyya & Strohmayer 2005b), which will be very useful for constraining neutron star mass and radius, and hence for understanding the dense cold matter at the stellar core (Bhattacharyya et al. 2005). The oscillation frequency of the observed burst seems to increase somewhat with time, and such evolution during burst rise can be used to understand the spreading of the thermonuclear flames on the neutron star surface (Bhattacharyya & Strohmayer 2005b; 2005c). Such an understanding (Spitkovsky, Levin, & Ushomirsky 2002; Bhattacharyya & Strohmayer 2005a; 2005c) may be useful for constraining stellar surface and structure parameters.

We also discovered intensity dips in the soft X-ray band from A1744–361, but have not observed any eclipses. This establishes that A1744–361 is a ‘pure’ dipper, which suggests that the observer’s inclination angle  $i$  is in the range  $\sim 60^\circ - 75^\circ$  (Frank et al. 1987).

Two subsequent sets of dips also suggest that the orbital period of this binary system is  $P = 97 \pm 22$  min, which is consistent with the observed orbital periods of other compact LMXB systems harboring rapidly rotating neutron stars. Using this orbital period and the equation  $P \approx 9^{\text{h}}(R_{\text{comp}}/R_{\odot})^{3/2}(M_{\odot}/M_{\text{comp}})^{1/2}$  (Bhattacharya & van den Heuvel 1991), we can draw a curve in the radius-mass plane of the secondary companion star. Here,  $9^{\text{h}}$  is 9 hours,  $R_{\text{comp}}$  &  $M_{\text{comp}}$  are the companion radius and mass, and  $R_{\odot}$  &  $M_{\odot}$  are the solar radius and mass. This radius-mass relation, and the obtained range of  $i$  would allow a determination of the nature of the companion star, if either the pulsar mass function or the projection of the orbital velocity of the neutron star along the line of sight were known. However, even with the available information, we can make some useful comments. To do this, we keep in mind that for a given nature and mass of the companion, if  $R_2$  is the normal stable radius, then the actual radius  $R_{\text{comp}}$  may be greater than or equal to  $R_2$  (due to bloating by X-ray heating), but can not be less than it. Consequently, if  $M_{\text{comp}} > 0.18M_{\odot}$ , the companion can not be a hydrogen main sequence star. As for  $M_{\text{comp}} > 0.18M_{\odot}$  a degenerate or helium main sequence companion would have to be bloated by at least several or many times its original volume, it is likely that  $M_{\text{comp}} < 0.18M_{\odot}$ . This suggests that the companion star in A1744–361 is likely to be a slightly bloated brown dwarf or hydrogen main sequence star (see Bildsten & Chakrabarty 2001).

We have also discovered low frequency QPOs ( $\sim 3$  Hz) for the first time from A1744–361. This is consistent with the fact that this source is a dipper, as such QPOs have been observed from other dipping LMXBs (Jonker et al. 2000). It has been proposed that these QPOs are caused by the partial obscuration of the central X-ray source by a nearly opaque or gray medium in or on the accretion disk (Jonker et al. 2000), that requires a high system inclination angle ( $i$ ), which is the case for a dipper. We also report an indication of a kHz QPO from this source, which if confirmed, would likely be a lower kHz QPO. If confirmed, this will be the first kHz QPO observed from A1744–361.

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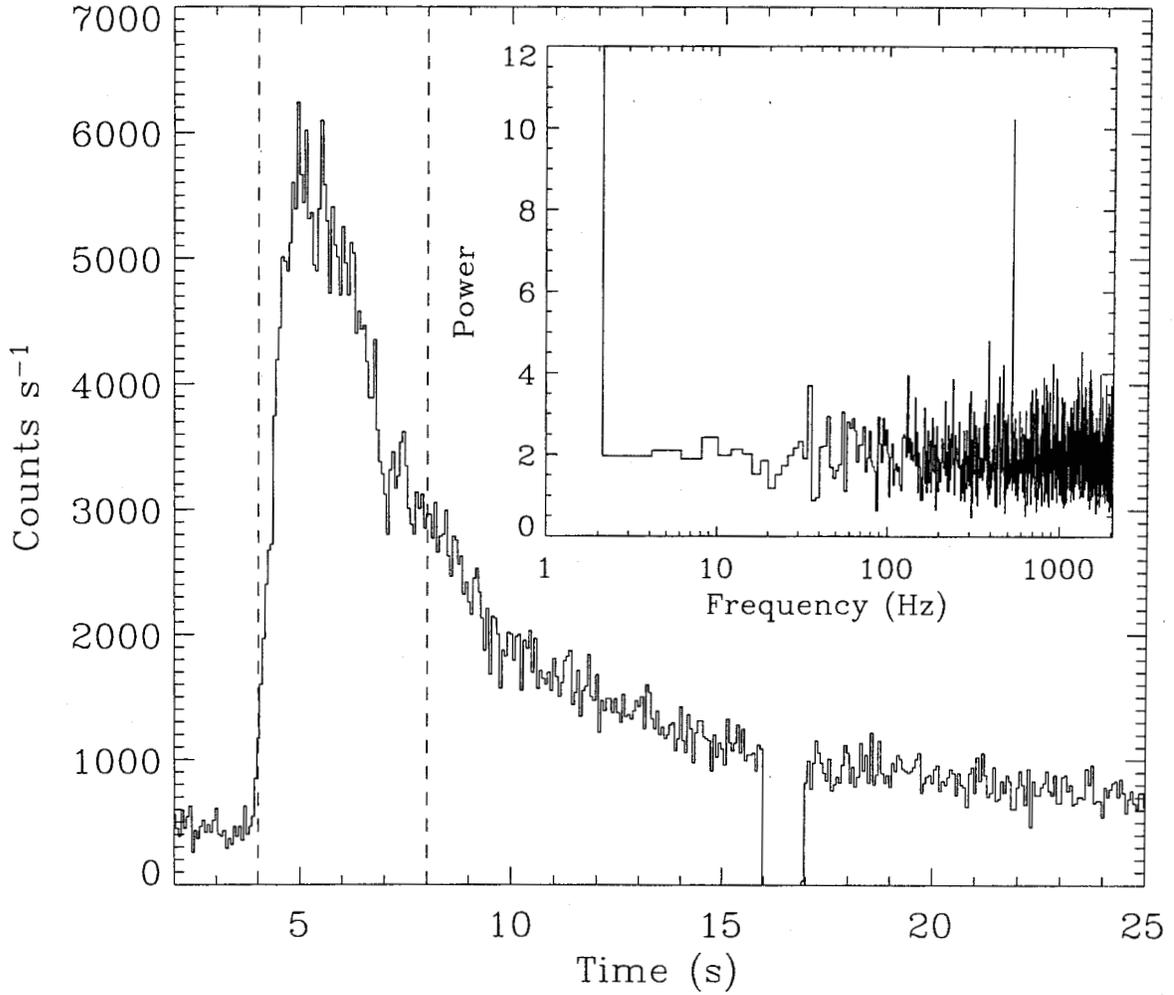


Fig. 1.— A thermonuclear X-ray burst from A1744-361. The main panel shows the PCA countrate (3 detectors operating) profile in the 2 - 60 keV band. The inset panel shows the power spectrum of the first 4 s interval (marked with vertical dashed lines in the main panel), rebinned to 2 Hz resolution. The peak near 530 Hz stands out well above the noise level.

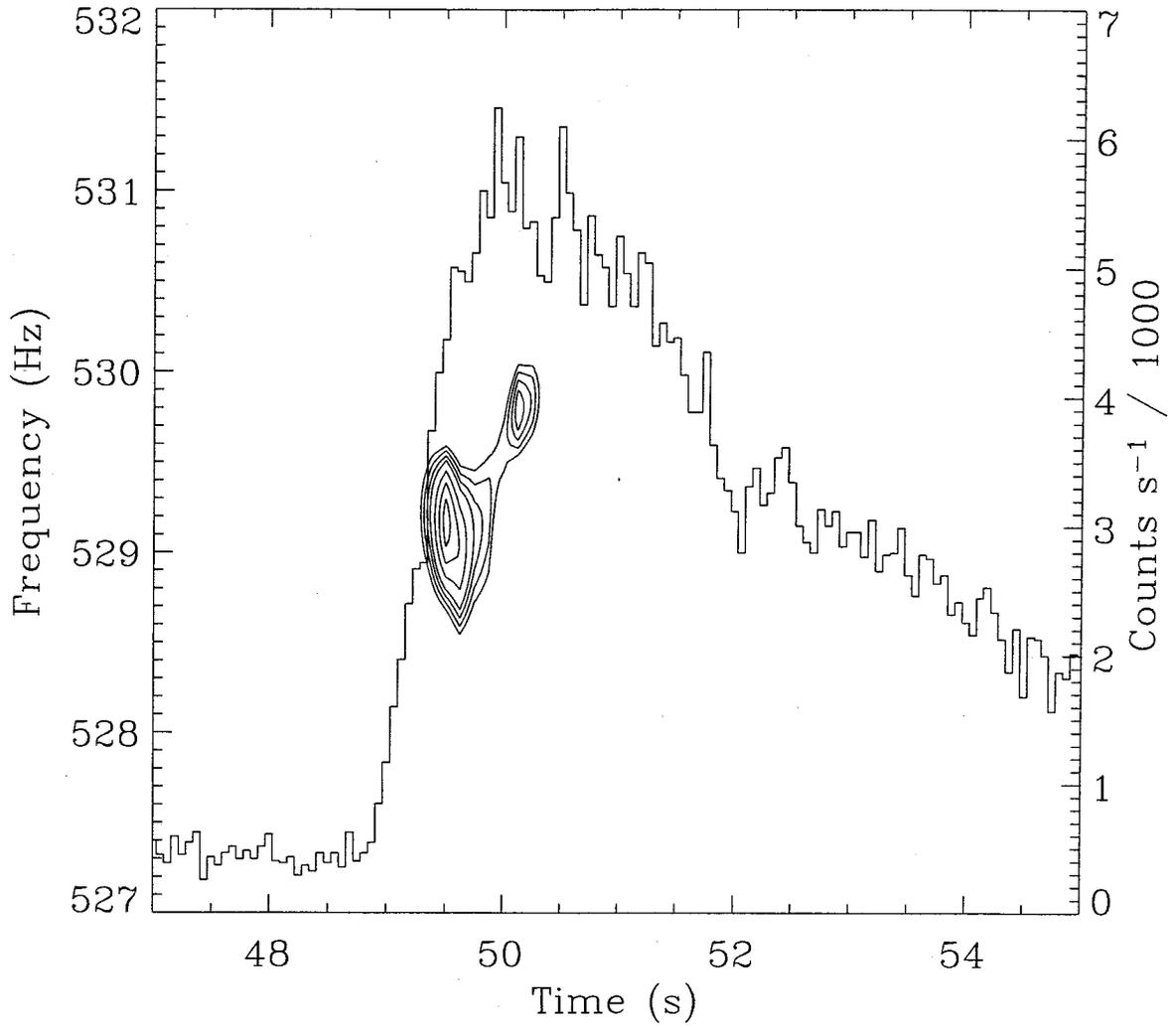


Fig. 2.— Dynamic power spectrum of the burst from A1744-361. Power spectra were computed using the  $Z^2$  statistic using 1 s intervals, with a new interval starting every 1/8 s. The energy band was 2 - 60 keV. Contour levels of  $Z^2 = 20, 22, 24, 26, 30, 34,$  and 38 are shown. The peak  $Z^2$  power was 41.1.

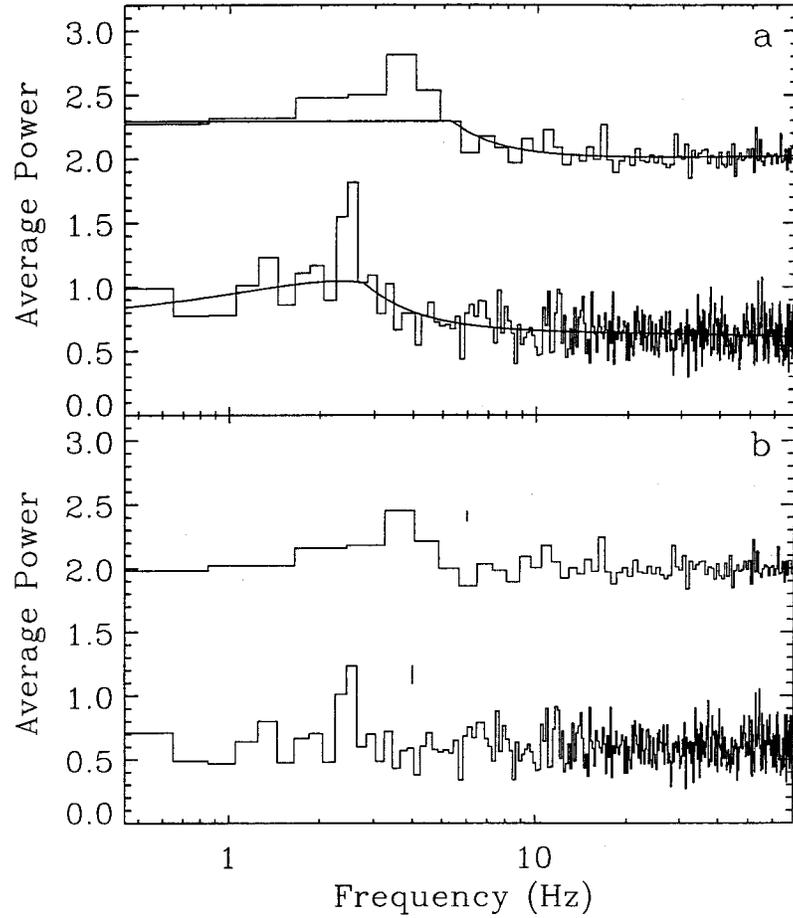


Fig. 3.— Low frequency quasi-periodic-oscillations (QPOs) from A1744-361. Panel *a* shows the power spectra for the ObsId 90058-04-01-00 (upper figure), and the ObsId 90058-04-02-00 (lower figure; power shifted by  $-1.4$ ). The solid curves give the best fit models of the continua. In panel *b*, each of these power spectra has been divided by the best fit model, and then multiplied by 2. The isolated vertical lines give the corresponding size of the  $1\sigma$  error. For these panels, powers are calculated for 10 s data segments, and averaged over  $M$  such segments. For the ObsId 90058-04-01-00,  $M = 75$ , and frequency resolution is 0.8 Hz, while these numbers are 100 and 0.2 Hz for the ObsId 90058-04-02-00.

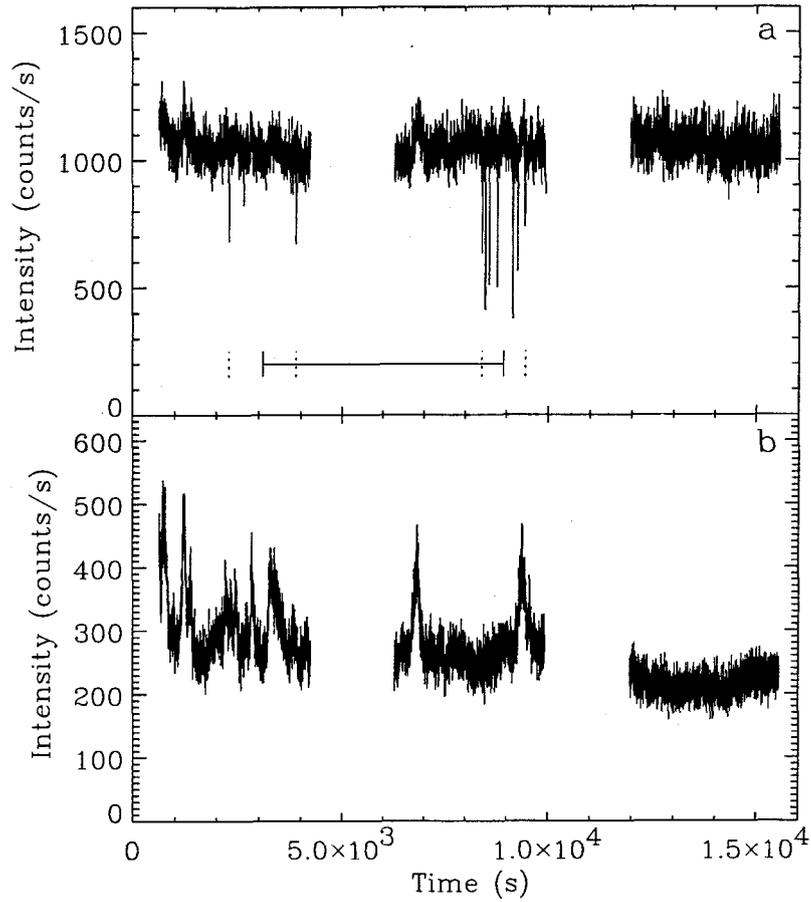


Fig. 4.— Energy dependent dips in the lightcurves from A1744–361. Both the panels are for three time segments of the ObsId 80431-01-02-00, the panel *a* is for the PCA channel range 0 – 13, while the panel *b* is for the channel range 14 – 63. Dips due to obstruction of the central source by the structures in accretion flow appear only in the soft energy lightcurves (panel *a*). The solid horizontal line in the panel *a* gives the approximate orbital period, and the dotted vertical lines give the corresponding uncertainties on both sides.