THE DISCOVERY OF A NEUTRON STAR WITH A SPIN FREQUENCY OF 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 they 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 ~97 minutes. We have also detected a 2–4 Hz quasi-periodic oscillation (QPO) for the first time from this source. This QPO appears consistent with ~1 Hz QPOs seen from other high-inclination systems. We searched for kilohertz QPOs and found a suggestive 2.3 σ 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 — rotation — X-rays: binaries — X-rays: bursts — RXTE

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1.INTRODUCTION

The X-ray transient A1744−361 was discovered by Ariel 5 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 yr later in 1989 August (in 't Zand 1992, 2004). This time it was detected by the COded Mask Imaging Spectrometer (COMIS/TTM; in 't Zand 1992) on board the Mir space station, and the source was at a relatively constant level of ~60 mcrab (about 3 times fainter than in 1976; see in 't Zand 1992). It was at least 10 times weaker (and undetectable) 5 months earlier and 1 month later (in 't Zand 2004). The source spectrum was indicative of a soft transient (in 't Zand 1992). Emelyanov et al. (2001) analyzed 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 1989 August 23 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, the X-ray detections (in 2003 and 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 2006; Liu et al. 2001). By analyzing 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 ~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 2006). Therefore, the burst oscillation frequency is identical to, or very close to, the stellar spin frequency. Hence, our detection of ~530 Hz burst oscillations establishes the spin frequency of the neutron star in A1744−361.

Analyzing 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 ± 22 minutes. We also report the discovery of a low-frequency quasi-periodic oscillation (QPO; ~3 Hz) as well as an indication of a kilohertz (kHz) QPO (~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.
We analyzed RXTE PCA data from the transient source A1744–361 when it was in outburst in 2003, 2004, and 2005. The durations (RXTE proposal number, RXTE observation duration) of these outbursts were ∼1 month (P80431, ∼39.1 ks), ∼20 days (P90058, ∼1.9 ks), and ∼40 days (P91050, ∼14 ks), respectively. We analyzed all the ∼55 ks of data and found a single thermonuclear X-ray burst (2005 July 16). The rise time of the burst is ∼1 s, while the decay time is ∼10 s (see Fig. 1). The peak count rate of the burst was ∼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 (for the fixed hydrogen column density 0.79 × 10^{22} cm\(^{-2}\); in ’t Zand 1992) through the burst. The lack of any significant drop in the blackbody temperature, correlated with an increase in the blackbody normalization (i.e., radius), leads us to conclude that this is not a photospheric radius expansion burst. The burst had a peak flux in the 2–20 keV band of ergs cm\(^{-2}\) s\(^{-1}\), and we calculated fast Fourier transforms on each time segment. 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 μs event mode data. We found a candidate peak at ∼530 Hz in the first such spectrum. The main panel of Figure 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 Figure 1 shows the 2 Hz resolution power spectrum. The probability of obtaining a power this high in a single trial from the expected χ\(^2\) noise distribution (16 degrees of freedom) is ≃6.13 × 10^{-11}. Multiplying by a conservative trial penalty of 8192, the number of frequency bins in the original spectrum, we arrive at a significance of 5.02 × 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 2 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 et al. 2003). The pulse profile is sinusoidal, with no indications of significant harmonic structure.

We searched all the data for QPOs and found an ∼3 Hz QPO in the 2004 April data. We divided 750 s of data from ObsID 90058-04-01-00 into M (=75) equal segments of 10 s duration, and we 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 histogram of Figure 3a shows this power spectrum, which clearly depicts a QPO of quality factor (Q) ∼2, at ∼3.5 Hz (rms amplitude ∼5%). For computing the significance of this QPO, we fitted the spectrum with a model and minimized the corresponding χ\(^2\) 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 histogram of Fig. 3b), in order to have the noise distributed as χ\(^2\) with 2MW degrees of freedom. The peak power (2.45) of the QPO, therefore, has the single trial significance of 1.25 × 10^{-7}. As low-frequency QPOs are searched up to 100 Hz, multiplying by the number (=125) of
that the orbital period of A1744.

width of each set of dips introduces an uncertainty, we suggest
period of the binary system (White & Swank 1982). As the
the two subsequent sets of dips gives an estimate of the orbital
Frank et al. 1987). The time separation (97 minutes) between
caused by cold clouds (or other structures) distributed in a range
obstruction of the central X-ray source by structures (above the
accretion disk plane) created within the accretion flow (White &
Swank 1982; Jonker et al. 2000). We found two sets of dips in
November 17). The observed durations of the dips are between
5 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 source by the structures in accretion
flow appear only in the soft energy light curves (panel a). The solid horizontal
line in panel a gives the approximate orbital period, and the dotted vertical
give the corresponding uncertainties on both sides.

trials, we get a significance of $1.56 \times 10^{-5}$, which implies an
$\sim 4.3 \sigma$ detection. We also note that this QPO seems to shift
by $\sim 1$ Hz in $\sim 40$ hr, as there is an indication of an $\sim 2.5$ Hz
QPO (with significance $\sim 2.6 \sigma$, and rms amplitude $\sim 3\%$; lower
histograms of Figs. 3a and 3b) in ObsID 90058-04-02-00 (2004
April 10).

We searched for kHz QPOs in the whole data set and found
a tentative indication of a 800 Hz QPO in 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 ObsID 80431-01-02-00 (2003
November 17). The observed durations of the dips are between
5 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, e.g.,
Frank et al. 1987). The time separation (97 minutes) 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 $97 \pm 22$ minutes. How-

ever, 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 a
putative type I X-ray burst; Emelyanov et al. 2001) that
A1744–361 is a neutron star LMXB. Since 2003, the source
has shown outbursts every year. Analyzing 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 to 619 Hz (Strohmayer & Bildsten 2006; Kaaret et al. 2006).
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 2005), which
will be very useful for constraining the 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

![Fig. 3.—Low-frequency QPOs from A1744–361. Panel a shows the power
spectra for ObsID 90058-04-01-00 (upper histogram) and ObsID 90058-04-
02-00 (lower histogram; 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 ObsID 90058-04-01-00, $M = 75$, and the frequency resolution
is 0.8 Hz; these numbers are 100 and 0.2 Hz for ObsID 90058-04-02-00.

![Fig. 4.—Energy-dependent dips in the light curves from A1744–361. Both
panels are for three time segments of ObsID 80431-01-02-00; panel a is for
the PCA channel range 0–13, while 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 light curves (panel a). The solid horizontal
line in panel a gives the approximate orbital period, and the dotted vertical
line gives the corresponding uncertainties on both sides.](Image)
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 2005, 2006b). Such an understanding (Spitkovsky et al. 2002; Bhattacharyya & Strohmayer 2006a, 2006b, 2006c) 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 $P = 97 \pm 22$ minutes, 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 $P \approx (9 \text{ hr})(R_{\text{comp}}/R_\odot)^{3/2}(M_\odot/M_{\text{comp}})^{1/2}$ (assuming that the donor star fills its Roche lobe; Bhattacharyya & van den Heuvel 1991), we can draw a curve in the radius-mass plane of the secondary companion star. Here $R_{\text{comp}}$ and $M_{\text{comp}}$ are the companion radius and mass, and $R_\odot$ and $M_\odot$ are the solar radius and mass, respectively. This radius-mass relation, and the obtained range of $i$, would allow us to determine 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 $R_i$ is the normal stable radius, then the actual radius $R_{\text{comp}}$ may be greater than or equal to $R_\odot$ (due to bloating by X-ray heating) but cannot be less than it. Consequently, if $M_{\text{comp}} > 0.18 M_\odot$, the companion cannot be a hydrogen main-sequence star. As for $M_{\text{comp}} > 0.18 M_\odot$, 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 $M_{\text{comp}} < 0.18 M_\odot$. 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). However, we note that if the actual orbital period is double the proposed one, the companion star may be a hydrogen main-sequence star (with the upper limit of $M_{\text{comp}} \approx 0.35 M_\odot$) or a brown dwarf, while an orbital period half the proposed value will allow for a brown dwarf and a hydrogen main-sequence star (for $M_{\text{comp}} < 0.1 M_\odot$), as well as a bloated helium main-sequence star with larger mass (maybe $>0.6 M_\odot$).

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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