ROSSI X-RAY TIMING EXPLORER DISCOVERY OF COHERENT MILLISECOND PULSATIONS DURING AN X-RAY BURST FROM KS 1731−260

DONALD A. SMITH,1 EDWARD H. MORGAN, AND HALE BRADT
Center for Space Research and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139

Received 1996 December 20; accepted 1997 February 3

ABSTRACT

A highly coherent 523.92 ± 0.05 Hz periodic X-ray signal has been observed during a type 1 X-ray burst from the low-mass X-ray binary system KS 1731−260 with the Proportional Counter Array on Rossi X-Ray Timing Explorer. The spectral evolution of the burst indicates photospheric-radius expansion and contraction. The 524 Hz signal occurred at the end of the contraction phase, lasted for ~2 s, was highly coherent (Q ≈ 900), and had a pulse fraction (ratio of sinusoidal amplitude to mean count rate) of 6.2% ± 0.6%. KS 1731−260 is one of only three systems that have exhibited high-coherence millisecond oscillations during X-ray bursts and the first reported in which the pulsations are associated with photospheric contraction. These coherent signals may be interpreted as a direct indication of the neutron star spin.

Subject headings: X-rays: bursts — X-rays: stars

1. INTRODUCTION AND OBSERVATIONS

Accreting low-mass X-ray binaries (LMXBs) may be the progenitors of the millisecond radio pulsars. The long life of these systems, during which angular momentum is transferred to the neutron star through accretion, is thought to lead to the millisecond spin periods observed in the fastest radio pulsars (Smarr & Blandford 1976; Bhattacharya 1995). Prior to the launch of the Rossi X-Ray Timing Explorer (RXTE), however, no convincing spin periods of less than 131 ms (in Aql X-1; Schoelkopf & Kelley 1991) had been found in any LMXB. High time resolution and large effective area give RXTE sensitivity to pulse frequencies into the kilohertz range, which allows users to search for coherent signals that might indicate neutron stars spinning with millisecond periods. Three examples of such signals have been reported: a 363 Hz (2.75 ms) oscillation in six bursts from 4U 1728−34 (Strohmayer et al. 1996b), a 524 Hz (1.91 ms) oscillation in a single burst from KS 1731−260 (Morgan & Smith 1996), and a 589 Hz (1.70 ms) oscillation in three bursts from an unidentified source near GRO J1744−28 (Strohmayer, Lee, & Jahoda 1996a). Here we provide a detailed report of the KS 1731−260 observation.

The Galactic X-ray source KS 1731−260 was first discovered in outburst during 1989 August with the imaging spectrometer TTM on the Mir-Kvant observatory (Sunyaev 1989). It was observed for 24 intervals of 1000 s each over the course of 15 days, and its intensity ranged from 50 to 100 mCrab in the 2−27 keV band. The spectrum of the persistent emission was found to be well fitted by a thermal bremsstrahlung model with a temperature of 5.7 ± 0.3 keV. Three type I X-ray bursts were observed from KS 1731−260 during this period. The bursts lasted 10−20 s each and reached intensities up to 0.6 Crab (Sunyaev et al. 1990b). The presence of type I bursts identified the compact object as an accreting neutron star. No pulsations were detected. In short, the source exhibited characteristics typical of a low-mass X-ray binary system (Barret et al. 1992).

Subsequent detections of KS 1731−260 were sporadic, which implied that the source is transient in nature. In 1990, the source was detected on two occasions (April 4 and August 23) by the ART-P imaging instrument aboard the Granat spacecraft (Sunyaev et al. 1990a, 1990b). In 1990 and 1991, the SIGMA telescope detected the source only once (on 1991 March 14 during an approximately 20 hr exposure) in a series of 20 observations of its location (Barret et al. 1992). It was also detected during the ROSAT all-sky survey (Predehl & Schmitt 1995).

Results from the RXTE All-Sky Monitor (ASM) reveal that KS 1731−260 is currently active. The source was detectable from the time of ASM turn-on in 1996 January through 1996 November with a typical intensity of ~160 mCrab (~1.5−12 keV). Further information about the ASM and its observations can be found in Levine et al. (1996) and also on the World Wide Web at http://space.mit.edu/XTE/XTE.html.

The ASM reports led us to request public observations of KS 1731−260 with RXTE’s Proportional Counter Array (PCA). Three observations with all five Proportional Counter Units (PCUs) were carried out for a total on-source time of 23,400 s, divided into 10 uninterrupted intervals. The Experiment Data System (EDS), the on-board computer that processes the data from the PCA, was configured to provide a primary data mode with 32 energy channels across the PCA’s energy range of ~2−90 keV and 62 μs (2−14 s) time resolution. This event mode will record only the first ~16,000 photons in any given second, but even at higher count rates, the event-mode data in a given second still provides useful rates. The arrival time of the last recorded photon is treated as the beginning of a data gap that ends with the beginning of the next second. To recover information lost in such a gap, we ran burst trigger and catcher modes in parallel with the event mode. The chosen burst catcher mode has a 125 μs time resolution but no energy resolution.

2. ANALYSIS AND RESULTS

During the 10 observing intervals, the total count rate of “good” events in the PCA from the typical source emission and background varied between 1619 and 3459 counts s−1. The
typical background rate was $\sim 130$ counts s$^{-1}$. The measured intensity above 27 keV was consistent with background during all observations. A single X-ray burst was observed during this program with onset at 1996 July 14 04:16:17.5 (UTC). The burst is displayed in Figure 1 in three different photon energy bands, which were selected such that each band has roughly the same count rate during the preburst emission. The spectrum of the emission immediately prior to the burst is well fitted (reduced $x^2 = 1.0$ for a 60 s exposure of one layer of one PCU) by an absorbed thermal bremsstrahlung model with a temperature of $kT = 5.5 \pm 0.2$ keV and a hydrogen column density of $(60 \pm 3) \times 10^{21}$ cm$^{-2}$.

The persistent emission data (2–27 keV) were searched for periodicities using a standard fast Fourier transform (FFT) algorithm. The time series were corrected for the difference in photon arrival time between Earth and the solar system barycenter with the Jet Propulsion Laboratory DE-200 solar system ephemeris (Standish et al. 1992). The 62 ms event-mode data were transformed in 64 s segments and were averaged together with appropriate weighting. The power of the Poisson noise was normalized to 2 in the power density spectra (PDS) (Leahy et al. 1983). No coherent periodic signals are detected in the PDS at any frequency of 4.4%. There is no evidence for any other periodicities in the frequency range of 15–8192 Hz (including harmonics of the 524 Hz signal) to 2 $\sigma$ upper limits on the pulse fraction at any frequency that increases from 4.4% to 12.9% with decreasing count rate, while the 2 $\sigma$ upper limit on the pulse fraction at 524 Hz varies between 1.5% and 5.0%.

It is highly improbable that the peaks at 524 Hz displayed in Figure 2 are due to random noise alone. The probability of a high (power $= P_0 \geq 29.75$) peak occurring at random in any one of the $N_{tot} = 81920$ independent frequency bins from the ten 1 s intervals is $\text{prob}(P_0 > P) = 1 - (1 - e^{-P_0/2})^{N_{tot}} = 0.0280$ (Vaughn et al. 1994). The probability of a second peak at $P_0 \geq 33.44$ appearing at random in the same frequency bin of an adjacent, independent PDS is only $1 - (1 - e^{-16.52})^2 = 1.1 \times 10^{-7}$.
The frequency of the pulsations was constrained by means of \( x^2 \) sinusoidal fits to the counts from the burst-catcher mode, which had no gaps at this high count rate. We split the 2 s interval into 0.5 s segments and found that the frequency is constant with a 1 \( \sigma \) upper limit on its rate of change of 0.5 Hz s\(^{-1}\). For the entire 2 s interval, the best-fit constant frequency is \( 523.92 \pm 0.05 \) Hz. The evolution of the pulsed amplitude was obtained from fits to 0.25 s intervals; it rose above a 1 \( \sigma \) detection at 04:16:20.0 \( \pm \) 0.25 s and fell below that level again at 04:16:22.0 \( \pm \) 0.5 s.

The energy dependence of the 524 Hz signal was obtained from sinusoidal fits to the event-mode data. The signal was strongest at higher energies (Fig. 3). At 7–27 keV, the pulse fraction is \( 9.0\% \pm 0.8\% \). At 2–7 keV, a 2 \( \sigma \) upper limit of 4.1% was obtained via the algorithm described in Chakrabarty et al. (1995).

The spectral evolution of the burst was studied through fits to the event-mode data in 0.25 s intervals over the course of the burst. Model spectra were folded through a PCA response matrix from a prerelease version of FTOOLS 3.6.1 (http://heasarc.gsfc.nasa.gov/docs/xte/whatsnew/software.html). A spectrum from a 1000 s interval immediately prior to the burst was subtracted from each of these spectra before any model fitting. This subtraction assumes that the mechanism that produces the preburst emission remains unaffected by the processes of the burst, which may not reflect the physics of the neutron star environment.

The best values of the reduced-\( x^2 \) statistic were achieved with a Planckian blackbody spectrum. The value for the column density \( N_H \) was fixed at the \textit{ROSAT} value of \( (10.0 \pm 1.9) \times 10^{21} \) cm\(^{-2}\) (Predehl & Schmitt 1995). The results of these fits are displayed in Figure 4. The somewhat high values of the reduced \( x^2 \) statistic appear to arise from systematic deviations of order \( \sim 20\% \) in the burst spectra from the Planckian model. Attempts to account for these deviations by adding a second continuum component were unsuccessful. A deviation in the form of a spectral hardening due to the dominance of electron scattering is expected at high luminosities (Castor 1974; London, Taam, & Howard 1984) and has been observed in bursts from other sources (see, e.g., van Paradijs et al. 1990). Our deviations show more structure than can be explained by a simple temperature shift, but in view of the relatively poor spectral resolution of this data mode, it seemed unproductive to apply multicomponent models with narrow spectral features to these deviations. Therefore, the radii and temperatures given in the figure must be considered uncertain in a systematic sense and treated with caution.

Spectral fits to other simple models such as thermal bremsstrahlung or a power law give reduced \( x^2 \) values higher by factors up to 32. Allowing \( N_H \) to float improved the bremsstrahlung fit to the same level as the blackbody fit at the cost of increasing \( N_H \) to \( (95 \pm 2) \times 10^{21} \) cm\(^{-2}\), which is inconsistent with the \textit{ROSAT} measurements.

The best-fit parameters from the Planckian models exhibit behavior expected from a radius-expansion burst (Fig. 4). Radius-expansion bursts are believed to occur when the luminosity of the burst reaches the Eddington limit and the atmosphere of the neutron star temporarily expands owing to radiation pressure (Lewin, Vacca, & Basinska 1984; Tawara et al. 1984). In this case, the \( \sim 0.75 \) s expansion phase is indicated by the increase of the normalization of the model (which represents the square of the blackbody radius at 10 kpc) and the corresponding decrease in the temperature. During the subsequent \( \sim 1.5 \) s contraction, the temperature increases as the atmosphere settles back to the surface. The temperature reaches a maximum as the radius reaches a minimum. Thereafter, the radius remains constant as the temperature de-
creases. The 2.0 s interval in which the 524 Hz oscillations appear is again marked by vertical dashed lines.

The best-fit spectral temperature is expected to be overestimated by a factor of approximately 1.4 at near-Eddington luminosities owing to the reduction of the radiation source function through electron scattering (London et al. 1984). The maximum effective temperature during this burst then becomes 1.7 ± 0.2 keV. Marshall (1982) calculates that black-body temperatures higher then 1.96 keV (for a helium-rich atmosphere; 1.67 keV for a hydrogen atmosphere) contradict the mass-radius relations derived from both soft and hard equations of state (Arnett & Bowers 1977) and are therefore impossible for a isotropically radiating neutron star to attain. The spectral hardening correction brings our maximum temperature into agreement with these limits.

The evolution of the blackbody luminosity follows from the temperature and the radius under the assumption of spherical symmetry (Fig. 4c). The luminosity during the expansion and contraction phases of the burst is consistent with a constant, as is expected if the burst is Eddington limited. Therefore, a rough estimate of the distance to the source can be calculated. For a 1.4 M_\odot neutron star with a helium-rich envelope, the Eddington luminosity as observed from a great distance is approximately 2.7 \times 10^{34} W (see, e.g., Haberl et al. 1987). The blackbody fits then yield a distance of 8.8 ± 0.3 kpc. At this distance, the “touchdown radius” indicated by the value of the normalization at the end of the contraction period is 9 ± 1 km. The spectral hardening at high luminosities would imply this result is underestimated by a factor of order 2. The errors are formal 90% confidence limits that include a 10% error estimate for the Eddington luminosity added in quadrature.

3. DISCUSSION

Rotational modulation of asymmetric emission is the simplest and most plausible mechanism for producing the observed 524 Hz oscillations. The high coherence (Q ≳ 900) of the peak argues for a highly coherent mechanism such as stellar rotation. The resulting spin period of 1.91 ms is consistent with predictions of spin periods in LMXBs (Smarr & Blandford 1976; Verbunt & van den Heuvel 1995) as well as the observed periods of millisecond “recycled” radio pulsars (see, e.g., Bhattacharya 1995; Backer et al. 1982; Fruchter, Stonebring, & Taylor 1988).

A key characteristic of the oscillations that any suggested model must explain is the point in the evolution of the burst at which they appear. No signal is seen during the rise of the burst, as would be expected if the asymmetry that gives rise to the modulation were due to a slowly propagating burning front as suggested by Bildsten (1995). Rather, the pulsations appear a full 2 s after the burning is over, at the end of the contraction phase, and they persist into the cooling phase. It is difficult to determine exactly when the pulsations vanish, as the detection threshold increases with decreasing count rate. All that can be said for certain is that they vanish during the cooling phase, for the 2σ upper limit on their pulse fraction in the persistent emission is 0.07% of the mean count rate.

It has been suggested (Marshall 1997) that the presence of a weak magnetic field could cause an anisotropy in the atmospheric opacity. Emission modulation due to this anisotropy would be visible if the atmospheric scale height were small, a vertical temperature gradient were present, and the magnetic field axis were not aligned with the rotation axis. We hypothesize that early in the burst, the atmosphere expands to a height at which the magnetic field is too weak to cause a significant opacity difference. As the energy from the burst is radiated away in the cooling phase, the atmosphere returns to its isothermal quiescent state, which would explain the disappearance of the pulsations in the burst as well as their absence at other times.

Observations of further bursts from this source should be performed to confirm this detection, but the results presented here suggest that radius-expansion bursts from other sources would be prime targets for RXTE to search for neutron star spin periods. A recent report of 589 Hz pulsations in radius-expansion bursts from an unidentified source near GRO J1744–28 (Strohmayer et al. 1996a) could be the second example of such a detection, as the pulsations in those bursts also begin several seconds after the burst rise is over. The 363 Hz pulsations from 4U 1728–34, on the other hand, seem more likely to arise from nuclear flash inhomogeneities. They appear during the burst rise, and they exhibit frequency evolution (Strohmayer et al. 1996b). Neither of these characteristics is displayed by the 524 Hz signal from KS 1731–260.

We are grateful to the entire ASM and RXTE engineering and science teams for their support. We thank in particular L. Bildsten, D. Chakrabarty, A. Levine, H. Marshall, R. Remillard, G. Rohrbach, A. Rots, R. Shirey, and L. Stella for their support. We thank in particular L. Bildsten, D. Chakrabarty, A. Levine, H. Marshall, R. Remillard, G. Rohrbach, A. Rots, R. Shirey, and L. Stella for their support.

REFERENCES

Arnett, W. D., & Bowers, R. L. 1977, ApJS, 33, 415
Backer, D. C., Kulkarni, S. R., Heiles, C. E., Davis, M. M., & Goss, W. M. 1982, Nature, 300, 615
Barret, D., et al. 1992, ApJ, 394, 615
Bhattacharya, D. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 233
Bildsten, L. 1995, ApJ, 438, 852
Castor, J. J. 1974, ApJ, 189, 273
Chakrabarty, D., et al. 1995, ApJ, 446, 826
Fruchter, A. S., Stonebring, D. R., & Taylor, J. H. 1988, Nature, 333, 237
Haberl, F., Stella, L., White, N. E., Friedhofer, W. C., & Gottwald, M. 1987, ApJ, 314, 266
Leahy, D., Darbrot, W., Elsner, R., Weisskopf, M., Sutherland, P., Kahn, S., & Grindlay, J. 1983, ApJ, 266, 160
Lewin, W. H. G., Vacca, W. D., & Basinska, E. M. 1984, ApJ, 277, L57
Levine, A., Bradt, H., Cui, W., Jerina, J. G., Morgan, E. H., Remillard, R., Shirey, R. E., & Smith, D. A. 1996, ApJ, 469, L33
London, R. A., Taam, R. E., & Howard, W. M. 1984, ApJ, 287, L27
Marshall, H. L. 1982, ApJ, 260, 815
———, 1997, in preparation
Morgan, E., & Smith, D. A. 1996, IAU Circ. 6437
Predehl, P., & Schmitt, J. H. M. H. 1995, A&A, 293, 889
Schoelkopf, R. J., & Kelley, R. L. 1991, ApJ, 375, 696
Smarr, L., & Blandford, R. 1976, ApJ, 207, 574
Standish, E. M., Newhall, X. X., Williams, J. G., & Ycomans, D. K. 1992, in Explanatory Supplement to the Astronomical Almanac, ed. P. K. Seidelmann (Mill Valley: University Science), 279
Strohmayer, T., Lee, U., & Jahoda, K. 1996a, 6484
Strohmayer, T., Zhang, W., Swank, J., Smile, A., Titarchuk, L., Day, C., & Lee, U. 1996b, ApJ, 469, L5
Sunyaev, R., et al. 1990b, IAU Circ. 4839
Sunyaev, R., et al. 1990a, IAU Circ. 5104
———, 1990b, Adv. Space Res., 11(8), 13
Tawara, Y., et al. 1984, ApJ, 276, L41
van Paradijs, J., Dotani, T., Tanaka, Y., & Tsuru, T. 1990, PASJ, 42, 633
Vaughn, B., et al., 1994, ApJ, 435, 362
Verbunt, F., & van den Heuvel, E. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 457