THE ASTROPHYSICAL JOURNAL, 518:L99–L102, 1999 June 20

DISCOVERY OF PULSED X-RAY EMISSION FROM THE SMALL MAGELLANIC CLOUD TRANSIENT RX J0117.6−7330

D. J. MACOMB,[1,2] M. H. FINGER,[2,3] B. A. HARMON,[3] R. C. LAMB,[4] AND T. A. PRINCE[4]

Received 1999 January 13; accepted 1999 April 14; published 1999 May 25

ABSTRACT

We report on the detection of pulsed, broadband, X-ray emission from the transient source RX J0117.6−7330. The pulse period of 22 s is detected by the *ROSAT*/PSPC instrument in a 1992 September 30–October 2 observation and by the *Compton Gamma-Ray Observatory*/BATSE instrument during the same epoch. Hard X-ray pulsations are detectable by BATSE for approximately 100 days surrounding the *ROSAT* observation (1992 August 28–December 8). The total directly measured X-ray luminosity during the *ROSAT* observation is 1.0×10^{38} (d/60 kpc)^2 ergs s^{-1}. The pulse frequency increases rapidly during the outburst, with a peak spin-up rate of 1.2×10^{-10} Hz s^{-1} and a total frequency change of 1.8%. The pulsed percentage is 11.3% from 0.1–2.5 keV, increasing to at least 78% in the 20–70 keV band. These results establish RX J0117.6−7330 as a transient Be binary system.

Subject headings: accretion, accretion disks — stars: individual (RX J0117.6−7330) — X-rays: general

1. INTRODUCTION

The PSPC instrument on board the *ROSAT* spacecraft made an 8.98 ks observation of the Small Magellanic Cloud on 1992 September 30–October 2, leading to the discovery (Clark, Remillard, & Woo 1996) of RX J0117.6−7330, a bright X-ray source within 5′ of SMC X-1. The source was not detected in an observation of the SMC 1 yr earlier and was found 246 days later to be dimmer by more than 2 orders of magnitude. The derived X-ray luminosity was 2.3×10^{37} (d/60 kpc)^2 ergs s^{-1} (0.2–2.5 keV; Clark, Remillard, & Woo 1997). Spectral analysis showed the source to be relatively soft, with a power-law index of around 2.7 (although a power law is not the best-fit model). A Fourier analysis did not reveal any significant periodicities, with the authors lamenting an increase in spectral noise at frequencies below 0.1 Hz.

The companion star first suggested by Clark et al. (1996) was observed by Charles, Southwell, & O'Donoghue (1996) optically in 1996 January. They determined that the B1–2 star of magnitude 14.2 proposed as the companion showed a strong IR excess and Balmer lines and a reddening typical of an OB star in the SMC, thus strengthening the association of the X-ray source with the SMC. They also argue that the luminosity and companion type indicates that the X-ray source is a neutron star (Coe et al. 1998). However, Clark et al. (1997) hypothesize that the system could harbor a black hole based on the e-folding X-ray decay time of 44 days, the rather soft spectrum, and the lack of any neutron star rotation period in the X-ray analysis.

We have performed a reanalysis of the *ROSAT*/PSPC data and have coupled it with hard X-ray observations by the *Compton Gamma-Ray Observatory* (*CGRO*)/BATSE instrument. In § 2, we present evidence for X-ray emission pulsed at a 22.067 s period that definitively establishes the X-ray source as a neutron star. We show the frequency history for RX J0117.6−7330 during this 100 day outburst, which reveals an extremely large average frequency derivative of 8.9×10^{-11} Hz s^{-1} corresponding to a spin-up timescale of 16 yr. The frequency derivative peaked at 1.2×10^{-10} Hz s^{-1}, with the pulse frequency increasing by 1.8% during the BATSE observations. The broadband X-ray pulse shapes and pulsed flux are calculated in § 3. Section 4 summarizes our findings and discusses RX J0117.6−7330 in the context of the Be class of high-mass X-ray binaries.

[1] Laboratory for High-Energy Astrophysics, NASA/Goddard Space Flight Center, Greenbelt, MD 20771.

[2] Astrophysics Program, University Space Research Association.

[3] Space Sciences Laboratory, ES 84, NASA/Marshall Space Flight Center, Huntsville, AL 35812.

[4] Space Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125.

2. PERIODICITY SEARCH

RX J0117.6−7330 was 5′ from the center of the PSPC field of view during an 8985 s exposure taken from MJD 48,895.7 to MJD 48,897.6 (MJD = JD −2,400,000.5). We determine a total source count rate of 4.43 ± 0.03 counts s^{-1} from 0.1 to 2.4 keV. Photons in a circle of radius 1′ surrounding the source position R.A., decl. (J2000) = ($01^h17^m36^s$, $-73°30'00''$) were extracted and barycentered using standard FTOOLS software. A total of 33,989 photons were available for timing analysis.

These photons were collected into 5 ms bins over the full length of the observation, a time span of 162 ks. A fast Fourier transform (FFT) of the resultant time series was then calculated, sensitive to periods in the range from 10 ms to 81,000 s with the power per channel normalized to unity using the average power for all frequencies above 0.01 Hz. No frequency derivatives were included at this point of the analysis. A peak of power 30, normalized as above, at a frequency of 0.090825(2) Hz was evident in this analysis and warranted further study despite increased noise due to the complicated *ROSAT* exposure-induced window function and spacecraft wobble.

Verification of the pulsed signal comes from an archival search of data from the BATSE instrument on *CGRO*. BATSE is capable of nearly continuous monitoring of hard X-ray sources using both the Earth occultation technique (Harmon et al. 1993) and timing techniques (Bildsten et al. 1997). A search of archival BATSE FFT results identified a possibly related outburst some 60 days after the 1992 *ROSAT* observation at a frequency of 0.0914825(2) Hz, with a frequency derivative of $9.7(2) \times 10^{-11}$ Hz s^{-1} consistent with the direction of the SMC. With follow-up epoch-folding–based searches of the BATSE data during the *ROSAT* observation, it became apparent that the originally detected frequency was the second harmonic of the pulse frequency. From 6 days of BATSE data centered on the *ROSAT* observation, a barycentric pulse frequency of 0.045316682(55) Hz (MJD 48,896.65) and frequency derivative of $9.81(8) \times 10^{-11}$ Hz s^{-1} were determined. Folding the

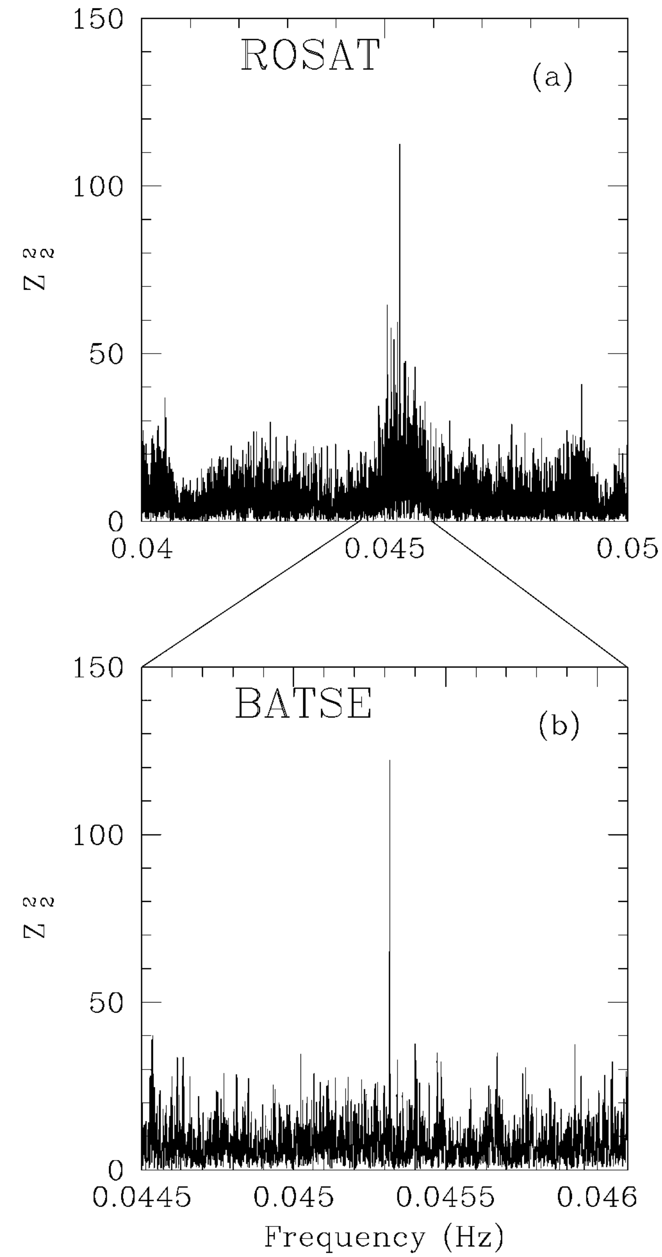

FIG. 1.—*ROSAT* power distribution encompassing the first harmonic of the pulsed frequency. The BATSE distribution is for a narrow range around the *ROSAT* detection frequency.

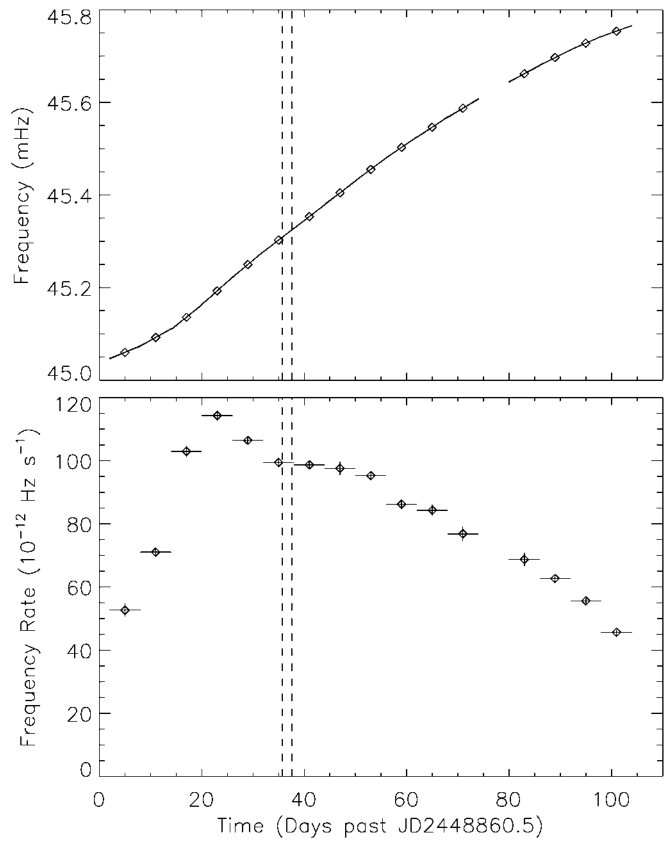

FIG. 2.—BATSE pulse timing analysis of RX J0117.6−7330. The top panel is the frequency history, and the bottom panel is the frequency rate history. Both plots use the best-fit values for 6 day intervals, with the *ROSAT* observation date shown by the dashed line.

ROSAT data with this frequency derivative gives a peak power at 0.0453168(3) Hz, consistent with the BATSE pulse period. Figure 1 shows the resultant *ROSAT* power spectrum calculated using the Z_2^2 statistic (Buccheri et al. 1983) over a narrow frequency range utilizing the above-stated frequency derivative. Also plotted is the same statistic for the BATSE data at frequencies near the *ROSAT* signal.

The results of searching the BATSE DISCLA channel 1 data (20–50 keV, 1.024 s resolution) from 1992 August 16 (MJD 48,850) to 1993 January 12 for pulsations from RX J0117−7730 are presented in Figure 2. These searches were performed in 6 day intervals, using an epoch-folding–based search (see Bildsten et al. 1997) that used only the first and second harmonic of the pulse profile and incorporated a search in both pulse frequency and frequency derivative. For intervals in which pulsations were detected, the pulse frequency and frequency derivative are shown. The frequency derivative peaks at 1.2×10^{-10} Hz s^{-1} 25 days before the 1992 *ROSAT* observations. The pulse frequency increases by 1.8% during the outburst. The signal is present for approximately 100 days, starting about 34 days before the *ROSAT*/PSPC observation.

3. BROADBAND PULSE PROFILE AND FLUX

Using the measured frequency and frequency derivative, we can construct the pulse profile for RX J0117.6−7330 for both soft and hard X-ray energies. Figure 3 shows both the *ROSAT*/PSPC pulse profile for 1992 September 30–October 2 (MJD 48,895–48,897) and the *CGRO*/BATSE profile for MJD 48,893.65–48,899.65. Both data sets use the pulse phase model based on the BATSE data. The optimal *ROSAT* frequency and frequency derivatives are slightly different. While the very high frequency derivative coupled with the long integration times (6 days for BATSE, 2 days for *ROSAT*) make absolute timing comparisons slightly problematic, there is no evidence for a loss of coherence in the BATSE folding, and the pulse phases from the two instruments should be directly comparable. Figure 3 shows the pulse shapes for both energy ranges using an epoch at phase zero of MJD 48,896.65. An extra phase offset of 0.14 was added in order to make the BATSE minimum correspond to phase zero. The overall profile shapes are similar. The peaks and minima of the light curves are generally in phase, but the primary peak in the *ROSAT*

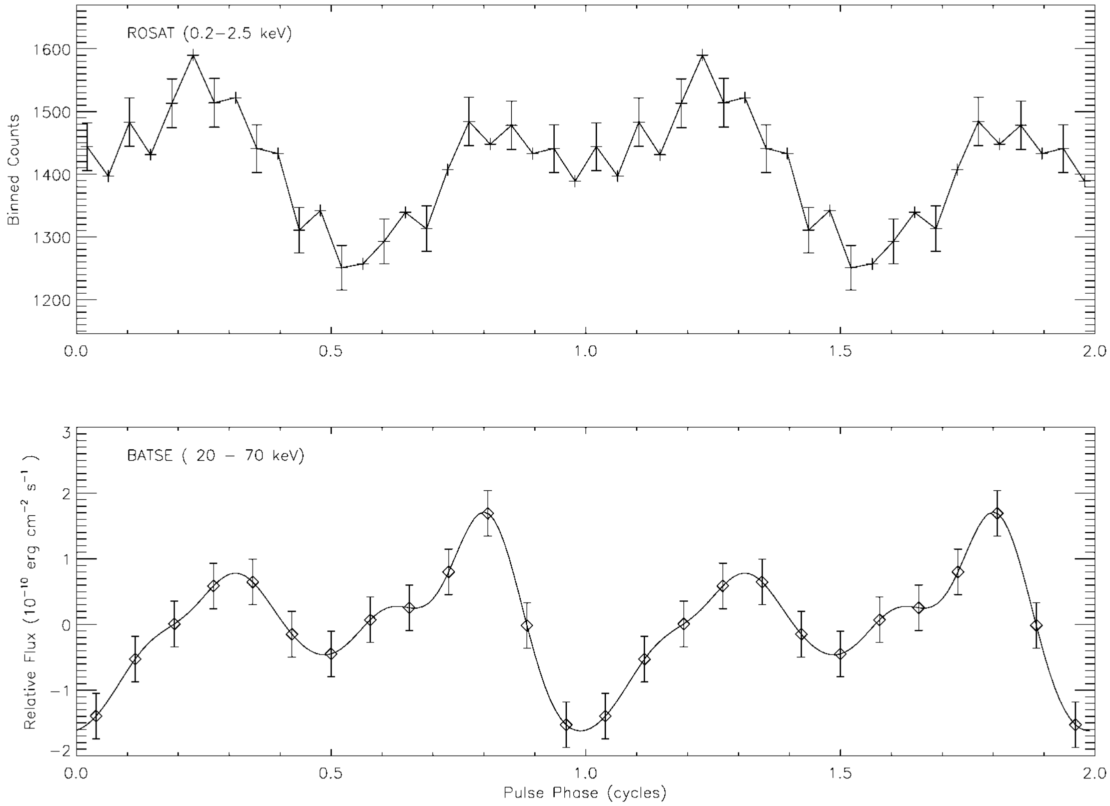

FIG. 3.—Folded light curves for *ROSAT* 0.1–2.4 keV (*top*) and BATSE 20–70 keV (*bottom*) data. The BATSE profile is limited to six Fourier harmonics, resulting in the smooth shape. Flux errors are given for a set of approximately independent phases.

energy range becomes the secondary peak in the BATSE range. Similarly, primary and secondary minima are interchanged.

We have tested our timing analysis methods using contemporaneous *ROSAT*/PSPC and *CGRO*/BATSE observations of PSR 1509−58. In this case, we find pulse profiles with shapes and radio-phase offsets consistent with previously published results (Greiveldinger et al. 1995; Ulmer et al. 1993). The overall pulse shape for RX J0117.6−7330 in both energy ranges is similar, so it is not out of the question that the shape as a whole has simply shifted. Apparent phase shifts of simple profiles in different energy bands have been previously observed. For example, the 1.2–2.3 and 18.4–27.5 keV profiles of GS 0834−430 observed with *Ginga* by Akoi et al. (1992) show a complex evolution with energy. It would be somewhat coincidental, however, for the phase shift to be such that the minima and maxima still coincide. At this point, we consider the peaks to be aligned, with the relative strengths to be changing.

From these pulse profiles, one may determine the pulsed flux and pulsed fraction. Using XSPEC, we calculate a total flux of $(5.1 \pm 0.3) \times 10^{-11}$ ergs cm^{-2} s^{-1}. Similar to Clark et al. (1997), we find that the best fit to the *ROSAT* spectrum is a combination of power law and bremsstrahlung or blackbody, although a straight power-law fit of index 2.65 ± 0.07 is not much worse. Of the 33,989 total counts extracted for the light curve, 3829 comprise the pulsed excess, giving a pulsed percentage of 11.3% ± 2.3%. This corresponds to a total pulsed flux in the 0.2–2.5 keV band of $(5.6 \pm 1.7) \times 10^{-12}$ ergs cm^{2} s^{-1}. In the BATSE energy range, the phase-averaged pulsed fraction is more difficult to assess. An occultation analysis of RX J0117.6−7330 detects a clear signal over the same time frame as the epoch-folding analysis. However, source confusion could significantly contribute to the detected flux. For a 20 day period around the time of the *ROSAT* observation, the average total flux is 0.012 ± 0.02 cm^{-2} s^{-1}. This corresponds to an energy flux of $(2.3 \pm 0.4) \times 10^{-10}$ ergs cm^{-2} s^{-1} (assuming a power-law index 3.0, 20–100 keV). The BATSE pulsed spectrum is best fit by a thermal bremsstrahlung model with temperature 18 ± 3 keV. The integrated 20–70 keV pulsed flux is $(1.8 \pm 0.2) \times 10^{-10}$ ergs cm^{-2} s^{-1} [7.8×10^{37} $(D/60\ \mathrm{kpc})^2$ ergs s^{-1}]. These values provide us with a lower limit to the pulsed fraction in the 20–70 keV range of 78% (a lower limit, since the measured occultation flux is considered to be an upper limit to total emission because of possible source confusion and the occultation analysis went up to 100 keV). The directly measured flux in the 0.2–2.5 and 20–70 keV bands alone is then at least $(2.3 \pm 0.2) \times 10^{-10}$ ergs cm^{2} s^{-1} [$(1.0 \pm 0.1) \times 10^{38}$ $(D/60\ \mathrm{kpc})^2$ ergs s^{-1}].

4. DISCUSSION

X-ray pulsations at a period of 22.07 s from the bright X-ray transient RX J0117.6−7330 have been detected in both the 0.1–2.4 and 20–70 keV energy bands. This confirms the identity of the X-ray source as a neutron star rather than a black hole. Transient X-ray pulsars are typically found in Be systems, which is consistent with, and supports the identification of, the proposed optical counterpart.

The *CGRO*/BATSE detection allows long-term monitoring of the outburst from this source. The hard X-rays are detectable for over 100 days starting 34 days before the *ROSAT* observation began. A large average spin-up is present over the duration of the outburst, resulting in a 1.8% change in frequency. The peak frequency changes appear 10–15 days before the *ROSAT* observation and approximately 20 days after the outburst began. Some of the frequency derivative may be caused by the binary orbit. Some of the variations seen in Figure 2 near the peak of the frequency derivative may be an orbital signature. Such variations are weak, however, compared to the overall accretion-induced changes in frequency.

The high intrinsic spin-up rates imply that an accretion disk is present about the neutron star, as is generally seen in the "giant" or type I outbursts of Be/X-ray pulsars (Bildsten et al. 1997). The measured luminosity is at least 1.0×10^{38} ergs s^{-1} during the *ROSAT* observation in the combined 0.2–2.5 and 20–70 keV bands. The peak frequency derivative was about 15% higher than during the *ROSAT* observation. However, we have no data in the energy range from 2.5–20 keV. With a complicated *ROSAT* X-ray spectrum and a changing pulse fraction, it is difficult to extrapolate our results to this energy range. However, it is likely that the luminosity in this range is comparable to that measured in the 0.2–2.5 and 20–70 keV ranges. Thus, the peak luminosity, when adjusted for higher frequency derivative and 2–20 keV emission, is $\geq 1 \times 10^{38}$ ergs s^{-1} and was probably higher than the conventional Eddington limit. This is consistent with the trend for Magellanic Cloud binaries to be much brighter on average than their Galactic counterparts—probably due to the absence of metals, which supply accretion-inhibiting absorption (Clark et al. 1978; van Paradijs & McClintock 1995). From the peak spin-up rate and standard accretion theory (Bildsten et al. 1997 and references therein), we can obtain a lower limit on the peak luminosity of $\sim 2.5 \times 10^{38}$ ergs s^{-1}. This is consistent with the highest luminosities of X-ray binaries in the SMC (van Paradijs & McClintock 1995). It is inconsistent with the source being in our Galaxy.

The pulse profiles in the two energy bands are similar in that they both have a double-peaked structure. However, the main and secondary peaks are interchanged. X-ray binaries typically have pulse profiles that are often strongly energy dependent (White, Swank, & Holt 1983). In this case, the double-peaked light curve in both energy bands shows the same peak-to-peak separation of 0.5. The pulsed fraction increases from 11% in soft X-rays to at least 78% in hard X-rays. If the overall morphology of the pulses is indeed the same, with the exception of the relative strengths of the two peaks, this may indicate a high magnetic field since at energies above the cyclotron energy, the pulse shape is expected to change significantly (e.g., see Sturner & Dermer 1994).

This project made use of software and data provided by the High-Energy Astrophysics Archival Research Center (HEASARC) located at Goddard Space Flight Center. This work was supported at Caltech in part by NASA NAG5-3239.

REFERENCES

Aoki, T., et al. 1992, PASJ, 44, 641
Bildsten, L., et al. 1997, ApJS, 113, 367
Buccheri, R., et al. 1983, A&A, 128, 245
Charles, P. A., Southwell, K. A., & O'Donoghue, D. 1996, IAU Circ. 6305
Clark, G., Doxsey, R., Lie, F., Jernigan, J. G., & van Paradijs, J. 1978, ApJ, 221, L37
Clark, G., Remillard, R., & Woo, J. 1996, IAU Circ. 6282
———. 1997, ApJ, 474, L111
Coe, M. J., Buckley, D. A. H., Charles, P. A., Southwell, K. A., & Stevens, J. B. 1998, MNRAS, 293, 43
Greiveldinger, C., Caucino, S., Massaglia, S., Ogelman, H., & Trussoni, E. 1995, ApJ, 454, 855
Harmon, A., et al. 1993, in AIP Conf. Proc. 280, *Compton Gamma-Ray Observatory*, ed. M. W. Friedlander, N. Gehrels, & D. J. Macomb (New York: AIP), 314
Sturner, S. J., & Dermer, C. D. 1994, A&A, 284, 161
Ulmer, M. P., et al. 1993, ApJ, 417, 738
van Paradijs, J., & McClintock, J. E. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 113
White, N. E., Swank, J. H., & Holt, S. S. 1983, ApJ, 270, 711