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DISCOVERY OF SUBMILLISECOND QUASI-PERIODIC OSCILLATIONS IN THE X-RAY FLUX OF SCORPIUS X-1

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ABSTRACT

We report the discovery, with NASA's Rossi X-Ray Timing Explorer (RXTE), of the first submillisecond oscillations found in a celestial X-ray source. The quasi-periodic oscillations (QPOs) come from Sco X-1 and have a frequency of ~1100 Hz and amplitudes of 0.6%–1.2% (rms) and are relatively coherent, with Q up to ~10^2. The frequency of the QPOs increases with accretion rate, rising from 1050 to 1130 Hz when the source moves from top to bottom along the normal branch in the X-ray color-color diagram, and shows a strong, approximately linear correlation with the frequency of the well-known 6–20 Hz normal/flaring-branch QPOs. We also report the discovery of QPOs with a frequency near 800 Hz that occur, simultaneously with the 1100 Hz QPOs, in the upper normal branch. We discuss several possible interpretations, one involving a millisecond X-ray pulsar whose pulses we see reflected off accretion flow inhomogeneities. Finally, we report the discovery of ~45 Hz QPOs, most prominent in the middle of the normal branch, which might be magnetospheric beat-frequency QPOs.

Subject headings: pulsars: general — stars: individual (Scorpius X-1) — stars: neutron

1. INTRODUCTION

The characteristic timescale for motion of matter near a gravitating object, the dynamical timescale τ_{dyn}, is $(r^3/GM)^{1/2}$, where r is the distance to the object and M is its mass. For $r = R$, the size of the object, τ_{dyn} is relevant to possible spin and vibration periods. For a neutron star, τ_{dyn} extends to values of well below 1 ms. Submillisecond variability could therefore be produced in an accreting neutron star by various mechanisms. In this Letter, we present the first conclusive evidence for submillisecond variability in an accreting neutron star, Sco X-1. A preliminary announcement of this work was already made in van der Klis et al. (1996).

Sco X-1 (see Giacconi et al. 1962), the brightest persistent X-ray source in the sky, is a Z source (Hasinger & van der Klis 1989), a luminous low-mass X-ray binary containing a low magnetic field neutron star. In the X-ray color-color diagram, it shows the lower two of the three branches in the canonical "Z track," the normal branch (NB) and the flaring branch (FB) (Middleditch & Priedhorsky 1986; Priedhorsky et al. 1986; Hertz et al. 1992; Dieters & van der Klis 1996). Its power spectrum is characterized by the presence of 1%–5% amplitude, 6–20 Hz normal/flaring-branch quasi-periodic oscillations (N/FBOs). According to the standard interpretation (see, e.g., Hasinger et al. 1990; Lamb 1991), when the mass transfer rate $\dot{M}$ to the neutron star increases, the source moves down along the NB, passes through the "vertex" of the two branches, where it reaches the Eddington critical rate, and

then moves up the FB. At the same time, the quasi-periodic oscillation (QPO) frequency increases from ~6 Hz on the NB to ~20 Hz on the lower FB. Further up the FB, the QPOs disappear. Below we report three new, previously unknown QPO phenomena in this source and describe their dependence on $\dot{M}$.

2. OBSERVATIONS

Sco X-1 was observed three times with the proportional counter array (PCA) on board NASA's Rossi X-Ray Timing Explorer (RXTE; see Bradt, Rothschild, & Swank 1993), on 1996 February 14 from 0914 to 1325 UT, February 18 0446–0840 UT, and February 19 1009–1456 UT, hereafter observations 1, 2, and 3, respectively. Each observation covered three satellite orbits with ~2500 s of data, separated by intervals of ~1500 s due to Earth occultation, South Atlantic Anomaly passage, or both. The count rate was ~10^5 counts s^{-1} in observations 1 and 2. At the start of orbit 1 of observation 3, the count rate increased to ~1.45×10^5 counts s^{-1}, which tripped the PCA high-voltage safety switch-off. RXTE was then moved slightly off Sco X-1 to ~50% collimator efficiency; later count rates were between 0.5×10^5 and 0.8×10^5 counts s^{-1}. The background below 20 keV was ≲90 counts s^{-1} and has been neglected.

During orbits 1 and 3 of each observation, data were collected with a time resolution of initially 0.5 ms and later, after discovery of the 1100 Hz QPOs in observation 1, usually
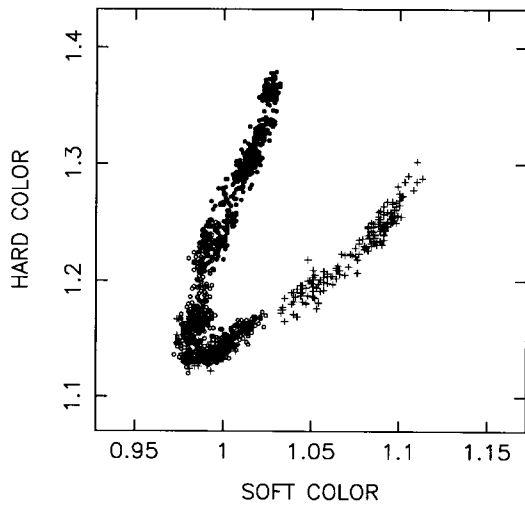
FIG. 1.—X-ray color-color diagram. Soft color is the (3–5 keV)/(1–3 keV), hard color the (7–20 keV)/(5–7 keV), count-rate ratio. Each data point corresponds to 16 s of data; filled circles, open circles, and plus signs correspond to observations 1, 2, and 3, respectively. The statistical uncertainties are ~0.003 in soft color and ~0.005 in hard color. The systematic uncertainties in Z-track location between observations (see § 3) are ~1%.

0.25 ms. During orbit 2 of each observation, the time resolution was set to 16 μs, and "double events" were additionally recorded at 64 μs time resolution. Double events, two events detected within 6 μs at two different anodes of a PCA detector, are normally mostly due to charged particles. However, for the very high count rates from Sco X-1, they are mostly due to two source photons. In the data analysis, the double events, counted as two, were added to the single-photon data. This led to a considerable increase in sensitivity to time variability. All high time resolution data were recorded in the 2–20 keV band. During the entire run, 16 s resolution data were additionally recorded in 129 spectral channels covering the 2–60 keV band.

3. ANALYSIS AND RESULTS

We used the 16 s data to construct X-ray color-color diagrams. There was a considerable offset between the Z track seen in observations 1 and 2 and that in observation 3, which we attribute to energy-dependent detector effects (collimator reflections, rate-dependent gains, or both). After an empirical correction that assumes that the Z track did not move between our observations (see, e.g., Dieters & van der Klis 1996), a typical Sco X-1 color-color diagram results (Fig. 1). During observation 1, the source moved gradually down the NB; during observation 2, it moved up and down between the lower NB and FB; and in observation 3, it moved gradually down the FB and into the vertex region. We assigned numbers S_Z to positions on the Z track according to curve length along the track, where we set the top of our NB to 1 and the vertex to 2.

Approximately 1100 Hz QPOs (Fig. 2) were observed on all occasions that the source was on the NB or very low on the FB and the observational setup was adequate (full collimator efficiency to ensure sufficient sensitivity, and sufficient time resolution). This was the case in orbit 2 of observation 1 and in orbits 1 and 2 of observation 2. The QPOs were seen independently in single- and double-event data. Table 1 lists the results of functional fits of a constant plus a power law plus one or two Lorentzian peaks to power spectra of the high time
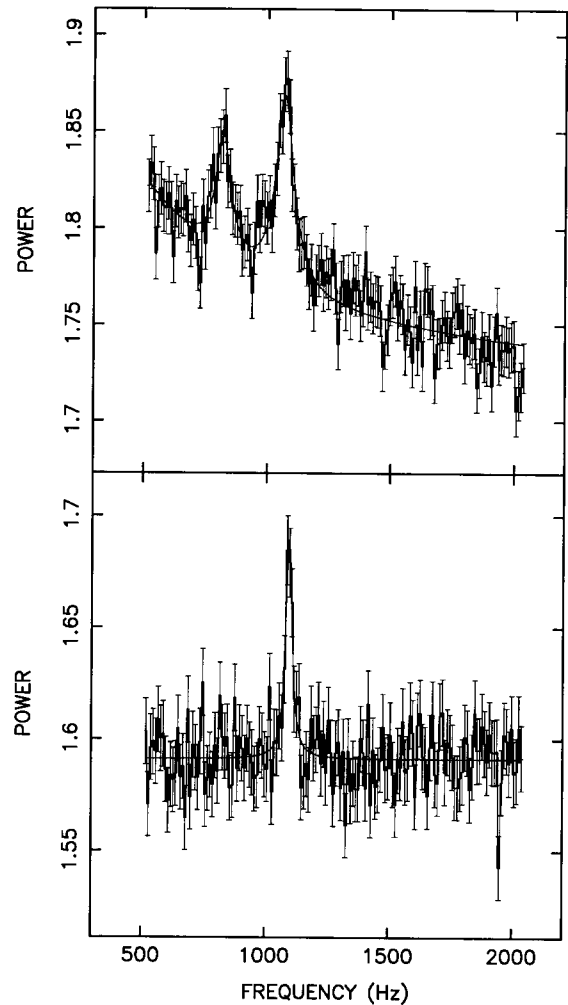

FIG. 2.—Power spectra of combined single- and double-event data (see § 2) showing simultaneous 800 and 1100 Hz QPOs (top; orbit 2 of observation 1) and a narrow 1100 Hz QPO peak (bottom; orbit 2 of observation 2). The spectra are Leahy-normalized; the offsets of the continua from a level of 2.0 and the slope of the continuum in observation 1 are due to instrumental dead-time effects.

resolution data. All fits were statistically acceptable, with reduced $\chi^2 \sim 1$. The QPO frequency ν_{1100} increased with $\dot{M}$, from 1050 Hz at $S_Z = 1.25$ to 1130 Hz at $S_Z = 2.1$. Note that, for lack of time resolution, we have no information about the 1100 Hz QPOs in the S_Z range 1.4–1.8. The QPOs were sometimes quite coherent, with $Q \equiv \nu/\Delta\nu$ up to 10^2. Fractional rms amplitudes, corrected for differential dead time (van der Klis 1989), assuming a paralyzable process (Zhang et al. 1995) with a dead time of 10 μs (Zhang 1995), ranged between 0.9% and 1.2% in observation 1 and 0.6% and 0.9% in observation 2. There was no clear dependence on $\dot{M}$ within each observation.

QPOs with a frequency of ~800 Hz were observed simultaneously with the 1100 Hz QPOs (Fig. 2, top) only when the source was in the upper NB ($S_Z < 1.36$). From studying the short-term power spectral variations, we can exclude that the two peaks are due to one peak moving in frequency, unless it moves on timescales shorter than 32 s. In orbit 2 of observation 1, the QPO frequency ν_{800} generally increased (from ~800 to

TABLE 1

QPO PARAMETERS

S_Z	1100 Hz		800 Hz		N/FBO	
	Frequency (Hz)	FWHM (Hz)	Frequency (Hz)	FWHM (Hz)	Frequency (Hz)	FWHM (Hz)
Observation 1, Orbit 2						
1.252 ± 0.027........	1050.3 ± 1.1	41 ± 5	803 ± 3	88 ± 11	4.9 ± 0.6	13 ± 3
1.282 ± 0.040........	1069.8 ± 8.2	104 ± 30	794 ± 20	145^{+189}_{-50}	6.06 ± 0.25	9.3 ± 1.1
1.336 ± 0.032........	1080.0 ± 4.8	50 ± 19	833 ± 12	80 fixed	5.74 ± 0.28	10.7 ± 1.1
1.340 ± 0.050........	1072.5 ± 5.4	78 ± 18	829 ± 5	49 ± 19	6.06 ± 0.22	8.5 ± 0.8
1.357 ± 0.022........	1069 ± 15	178^{+149}_{-65}	820 ± 12	80 fixed	5.64 ± 0.27	9.9 ± 1.1
Observation 2, Orbit 2						
1.866 ± 0.022........	1091.4 ± 1.8	22 ± 5	$\cdots$	$\cdots$	7.85 ± 0.04	4.44 ± 0.12
1.929 ± 0.050........	1100.8 ± 2.0	18 ± 4	$\cdots$	$\cdots$	9.42 ± 0.07	7.24 ± 0.23
Observation 2, Orbit 1						
1.966 ± 0.032........	1090.1 ± 2.3	18 ± 6	$\cdots$	$\cdots$	7.66 ± 0.09	5.81 ± 0.27
2.057 ± 0.006........	1129.7 ± 2.3	$13.4^{+6.2}_{-1.4}$	$\cdots$	$\cdots$	13.64 ± 0.17	6.6 ± 0.6
2.092 ± 0.025........	1135 ± 13	68^{+88}_{-40}	$\cdots$	$\cdots$	13.46 ± 0.04	9.60 ± 0.18

NOTES.—Fitting function: see § 3. All errors correspond to unreduced $\Delta\chi^2 = 1$. Fit range, frequency resolution, and number of degrees of freedom for the 1100 and 800 Hz QPO fits were 200–2000 Hz, 10 Hz, and 171 for observation 1, orbit 2; 512–1536 Hz, 5 Hz, and 200 for observation 2, orbit 1; and 200–2000 Hz, 5 Hz, and 356 for observation 2, orbit 2, respectively.

~830 Hz) when S_Z rose from 1.25 to 1.35 (ν_{1100} increased from 1050 to 1075 Hz over the same range). The 800 Hz QPOs were relatively broad, from 50 Hz to greater than 100 Hz, and had amplitudes between 0.9% and 1.2% (rms), decreasing slightly with S_Z. In orbit 1 of observation 1 ($S_Z < 1.16$), the sensitivity was less due to the lack of double-event data, but there was some evidence (3 σ) for the presence of a broad peak near 720 Hz.

A third new QPO feature, located near 45 Hz, was detected on the NB. These QPOs had an FWHM of typically 15–25 Hz and an amplitude of ~1% (rms) and were most prominent on the middle of the NB, near $S_Z = 1.5$. They were detected all the way from $S_Z = 1.1$ to 1.9 with little change in frequency. Figure 3 shows the power spectrum of data obtained in orbit 3 of observation 1, with 6 Hz QPOs (the N/FBOs) and 45 Hz QPOs.

The dependencies of ν_{1100} and the N/FBO frequency $\nu_{N/FBO}$ on S_Z are very similar. The relation between ν_{1100} and $\nu_{N/FBO}$ is plotted in Figure 4. There is a strong correlation. The relation fits a straight line, with $\nu_{1100} = 7.3\nu_{N/FBO} + 1032$; a power law fits as well.

4. DISCUSSION

The discovery of near-millisecond (Strohmayer, Zhang, & Swank 1996b; van Paradijs et al. 1996) and submillisecond (van der Klis et al. 1996) oscillations from accreting low magnetic field neutron stars was expected on the basis of general arguments (see § 1). To find and study such phenomena was one of the primary objectives of the *RXTE* mission. There is a range of phenomena that could take place on these timescales, and we shall not attempt to be exhaustive here. The
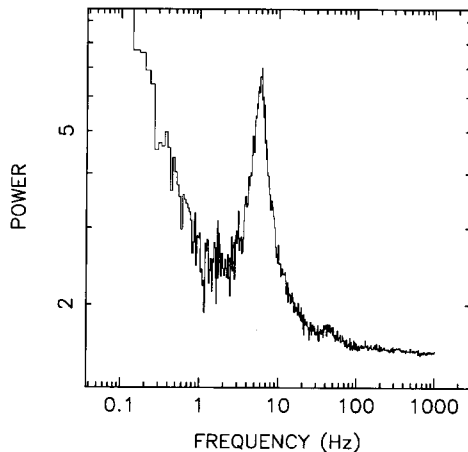

FIG. 3.—Power spectrum of 0.5 ms resolution data obtained in orbit 3 of observation 1, showing a strong N/FBO peak centered on 6 Hz and a weaker feature near 45 Hz. The spectrum is Leahy-normalized; the offset of the continuum from a level of 2.0 is due to dead-time effects.
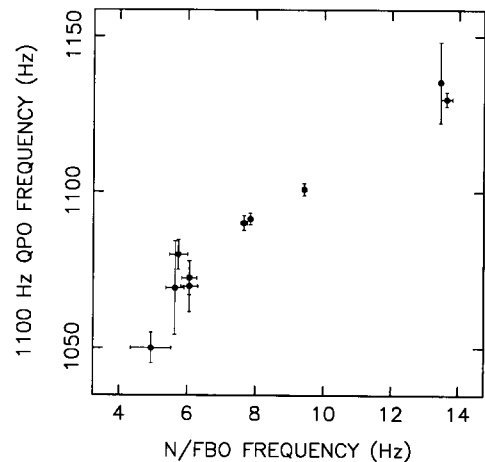

FIG. 4.—Relation between the frequencies of the 1100 Hz QPOs and the N/FBOs as derived from data in which these two phenomena were detected simultaneously. A strong correlation is evident.

fact that both ν_{1100} and ν_{800} increase considerably as a function of $\dot{M}$ suggests an origin in accretion phenomena rather than neutron star vibrations (e.g., McDermott, Van Horn, & Hansen 1988). Therefore, we concentrate on that class of models.

Disk frequency.—The Kepler frequency ν_K at the inner edge of the accretion disk, bounded by a small (16–20 km) magnetosphere, is in the correct range to be identified with either ν_{1100} or ν_{800}. It would increase with $\dot{M}$, as observed. The $\dot{M}$-dependence of the 800 Hz QPOs, strongest at low $\dot{M}$ and disappearing toward higher $\dot{M}$, is reminiscent of the "horizontal-branch QPOs" (HBOs) in other Z sources (van der Klis et al. 1985; see van der Klis 1995 for a review). These HBOs, in the beat-frequency model (Alpar & Shaham 1985; Lamb et al. 1985), are caused by "clumps" in the inner disk, which are most prominent at the lowest $\dot{M}$-levels. The 800 Hz QPOs (or, alternatively, the 1100 Hz QPOs) could be a direct signal from these clumps, either by reflection or obscuration of the X-ray flux from the central regions or by interaction with azimuthal structure in the radial flow (see below).

Beat frequency.—As no HBOs have been detected as yet from Sco X-1, an alternative possibility is that the 800 Hz QPOs are HBOs and that their frequency is the beat frequency $\nu_B = n(\nu_K - \nu_s)$ between ν_K and the neutron star spin frequency ν_s, where n is the field symmetry factor. This would make the HBOs in Sco X-1 *much* faster than those in other Z sources, whose frequency is 15–55 Hz, and would require a relatively slow neutron star spin rate (not more than a few hundred hertz). When this Letter was about to be submitted, the detection was reported in 4U 1728−34 of 363 Hz oscillations during X-ray bursts (Strohmayer et al. 1996a), which were interpreted as being due to the neutron star spin, and of two variable-frequency QPO peaks (one of which is the ~800 Hz QPO reported by Strohmayer et al. 1996b) whose separation remained near 363 Hz. Clearly, this suggests a beat-frequency model interpretation with ν_B, ν_K, and ν_s all visible. In the case of Sco X-1, the difference $\nu_{1100} - \nu_{800}$ is consistent with being constant near 250 Hz, but the range in frequencies over which both peaks are detected simultaneously is too small to draw any strong conclusion from this; there is no evidence for an oscillation near 250 Hz.

The new 45 Hz QPOs in Sco X-1 *are* in the range of HBO frequencies seen in the other Z sources. The dependence of their amplitude on S_Z is clearly different from that of HBOs in GX 5−1 and Cyg X-2, which are strongest at the top of the NB (and in the HB), not in the middle of the NB. In GX 17+2, 60 Hz QPOs have been discovered in the NB, which may be a similar phenomenon (Wijnands et al. 1996). If the 45 Hz QPOs in Sco X-1 are beat-frequency QPOs, then from the fact that its frequency is approximately constant we conclude that

the 1100 and 800 Hz QPOs, whose frequencies vary by tens of hertz, cannot be the disk frequency.

Doppler-shifted pulsar.—The strong correlation we observe between ν_{1100} and $\nu_{N/FBO}$ is not explained by any of the models discussed above. It could in principle arise because both frequencies vary as a function of $\dot{M}$ independently of each other, but this seems unlikely. The $\nu_{N/FBO}$ versus S_Z relation is known to jump at $S_Z = 2$ (see, e.g., van der Klis 1995), and ν_{1100} should then, independently, show a similar jump in its dependence on S_Z to maintain the correlation. It seems more likely that one frequency is by some mechanism directly derived from the other.

We briefly explore a mechanism in which this is the case. In the Fortner, Lamb, & Miller (1989) model for N/FBOs, part of the accretion takes place by way of an approximately radial inflow, and blobs (inhomogeneities) in this flow produce the N/FBOs. For a constant-size radial flow, $\nu_{N/FBO}$ is proportional to the inflow velocity v_r. If the 1100 Hz QPOs are the Doppler-shifted pulsar signal, which we see reflected off blobs in the flow, then when v_r varies, ν_{1100} should vary linearly with $\nu_{N/FBO}$, as observed. For a blob moving toward the star along a radial vector that makes an angle ϕ with the line of sight, ν_{1100} should be proportional to $[1 + (1 - \cos\phi)v_r/c]\nu_{puls}$, where ν_{puls} is the pulse frequency. Radial flow velocities up to at least $0.04c$ and spin frequencies of ~500 or ~1000 Hz, depending on whether one or two magnetic poles contribute to the signal, are required for this model to work. To obtain the relatively coherent QPO signal we observe, the range of angles ϕ contributing to the signal should be small. This would be true, for example, if the magnetic and rotation axes were nearly aligned. Aligned rotation would also explain why millisecond pulsars in low-mass X-ray binaries have been hard to find. This model would require a spin period ~1 ms, faster than any neutron star spin yet measured, as only one pole would contribute (the other pole could produce another QPO peak).

Note added in manuscript.—Further *RXTE* observations of Sco X-1 on May 24–25 again show the two high-frequency QPO peaks, this time with frequencies near 900 and 600 Hz. Their separation is significantly (>10 σ) larger than in the February observations. This excludes the beat-frequency interpretation in which the peak separation is predicted to be constant at the neutron star spin frequency.

REFERENCES

Alpar, M. A., & Shaham, J. 1985, Nature, 316, 239
Bradt, H. V., Rothschild, R. E., & Swank, J. H. 1993, A&AS, 97, 355
Dieters, S., & van der Klis, M. 1996, A&A, submitted
Fortner, B. F., Lamb, F. K., & Miller, G. S. 1989, Nature, 342, 775
Giacconi, R., Gursky, H., Paolini, F., & Rossi, B. 1962, Phys. Rev. Lett., 9, 439
Hasinger, G., & van der Klis, M. 1989, A&A, 225, 79
Hasinger, G., van der Klis, M., Ebisawa, K., Dotani, T., & Mitsuda, K. 1990, A&A, 235, 131
Hertz, P., Vaughan, B., Wood, K. S., Norris, J. P., Mitsuda, K., Michelson, P. F., & Dotani, T. 1992, ApJ, 396, 201
Lamb, F. K. 1991, in Neutron Stars: Theory and Observation, ed. J. Ventura & D. Pines (NATO ASI Ser. C, 344) (Dordrecht: Kluwer), 445
Lamb, F. K., Shibazaki, N., Alpar, M. A., & Shaham, J. 1985, Nature, 317, 681
McDermott, P. N., Van Horn, H. M., & Hansen, C. J. 1988, ApJ, 325, 725
Middleditch, J., & Priedhorsky, W. C. 1986, ApJ, 306, 230
Priedhorsky, W. C., Hasinger, G., Lewin, W. H. G., Middleditch, J., Parmar, A., Stella, L., & White, N. 1986, ApJ, 306, L91

Strohmayer, T., Zhang, W., Smale, A., Day, C., Swank, J., Titarchuk, L., & Lee, U. 1996a, IAU Circ. 6387
Strohmayer, T., Zhang, W., & Swank, J. 1996b, IAU Circ. 6320
van der Klis, M. 1989, in Timing Neutron Stars, ed. H. Ögelman & E. P. J. van den Heuvel (NATO ASI Ser. C, 262) (Dordrecht: Kluwer), 27
———. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 252
van der Klis, M., Jansen, F., van Paradijs, J., Lewin, W. H. G., van den Heuvel, E. P. J., Trümper, J. E., & Sztajno, M. 1985, Nature, 316, 225
van der Klis, M., Swank, J., Zhang, W., Jahoda, K., Morgan, E., Lewin, W., Vaughan, B., & van Paradijs, J. 1996, IAU Circ. 6319
van Paradijs, J., et al. 1996, IAU Circ. 6336
Wijnands, R. A. D., van der Klis, M., Psaltis, D., Lamb, F. K., Kuulkers, E., Dieters, S., van Paradijs, J., & Lewin, W. H. G. 1996, ApJ, 469, L5
Zhang, W. 1995, XTE/PCA internal memo.
Zhang, W., Jahoda, K., Swank, J. H., Morgan, E. H., & Giles, A. B. 1995, ApJ, 449, 930