THE ASTROPHYSICAL JOURNAL, 481:L97–L100, 1997 June 1
© 1997. The American Astronomical Society. All rights reserved. Printed in U.S.A.

KILOHERTZ QUASI-PERIODIC OSCILLATION PEAK SEPARATION IS NOT CONSTANT IN SCORPIUS X-1

MICHIEL VAN DER KLIS AND RUDY A. D. WIJNANDS
Astronomical Institute "Anton Pannekoek," University of Amsterdam, and Center for High-Energy Astrophysics, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands; michiel@astro.uva.nl, rudy@astro.uva.nl

KEITH HORNE
School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews KY16 9SS, Scotland, UK; kdh1@st-andrews.ac.uk

AND

WAN CHEN
NASA/GSFC Laboratory for High-Energy Astrophysics, Goddard Space Flight Center, Greenbelt, MD 20771; chen@rosserv.gsfc.nasa.gov
Received 1997 February 7; accepted 1997 March 10

ABSTRACT

We report on a series of 20, $\sim 10^5$ counts s^{-1}, 0.125 ms time-resolution *Rossi X-Ray Timing Explorer* observations of the *Z*-source and low-mass X-ray binary Scorpius X-1. Twin kilohertz quasi-periodic oscillation (QPO) peaks are obvious in nearly all observations. We find that the peak separation is not constant, as expected in some beat-frequency models, but instead varies from ~310 to ~230 Hz when the centroid frequency of the higher frequency peak varies from ~875 to ~1085 Hz. We detect none of the additional QPO peaks at higher frequencies predicted in the photon bubble model (PBM), with best-case upper limits on the peaks' power ratio of 0.025. We do detect, simultaneously with the kilohertz QPO, additional QPO peaks near 45 and 90 Hz whose frequency increases with mass accretion rate. We interpret these as first and second harmonics of the so-called horizontal-branch oscillations that are well known from other *Z*-sources and usually interpreted in terms of the magnetospheric beat-frequency model (BFM). We conclude that the magnetospheric BFM and the PBM are now unlikely to explain the kilohertz QPO in Sco X-1. In order to succeed in doing so, *any* BFM involving the neutron star spin (unseen in Sco X-1) will have to postulate at least one *additional* unseen frequency, beating with the spin to produce one of the kilohertz peaks.

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

1. INTRODUCTION

Kilohertz quasi-periodic oscillations (QPOs) have now been observed in 11 low-mass X-ray binaries, the *Z*-sources Scorpius X-1 (van der Klis et al. 1996a, hereafter Paper I), GX 5−1 (van der Klis et al. 1996c), and GX 17+2 (van der Klis et al. 1997), the atoll sources (see Hasinger & van der Klis 1989) 4U 1728−34 (Strohmayer et al. 1996b), 4U 1608−52 (Berger et al. 1996), 4U 1636−53 (Zhang et al. 1996), 4U 0614+09 (Ford et al. 1997), 4U 1735−44 (Wijnands et al. 1996b), and 4U 1820−30 (Smale, Zhang, & White 1996), and in KS 1731−260 (Morgan & Smith 1996) and a source near the Galactic center, perhaps MXB 1743−29 (Strohmayer, Lee, & Jahoda 1996a). In most of these sources, the QPO frequency has been observed to increase with accretion rate $\dot{M}$; frequencies are in the range 325–1193 Hz, and relative peak widths vary between 0.11% and 10%. Most often, *double* peaks are observed, with a separation in the range 250–360 Hz. In 4U 1728−34 (Strohmayer et al. 1996b), during X-ray bursts, a third peak is seen near a frequency of 360 Hz, compatible with the separation of the two kilohertz peaks, that remains constant as the peaks move up and down in frequency. Three other cases of three, similarly commensurate frequencies have been reported (4U 0614+09; Ford et al. 1997, 4U 1636−53; Zhang et al. 1997, and KS 1731−260; Wijnands & van der Klis 1997). This strongly suggests a beat-frequency interpretation, with the ~360 Hz peak in 4U 1728−34 at the neutron star spin frequency, the higher frequency (hereafter "upper") kilohertz peak at the Kepler frequency corresponding to some preferred orbital radius around the neutron star, and the lower frequency (hereafter "lower") kilohertz peak at the difference frequency between these two. Strohmayer et al. (1996b) suggested that this preferred radius is the magnetospheric radius. Miller, Lamb, & Psaltis (1997) proposed that it is the sonic radius.

Although ways out can always be found, this class of models naturally predicts the peak separation to be constant. In this Letter, we present data that show conclusively that in Sco X-1, the peak separation varies systematically. A brief announcement of this result already appeared in van der Klis et al. (1996b). We also present evidence for the presence of horizontal-branch oscillations (HBOs; see van der Klis 1995 for a recent summary of *Z*-source characteristics) in Sco X-1 near 45 Hz with a harmonic near 90 Hz. This is the first time that HBOs have been positively identified in Sco X-1. HBOs are usually interpreted in terms of the magnetospheric beat-frequency model (Alpar & Shaham 1985; Lamb et al. 1985), precluding the application of this model to the kilohertz QPOs that occur at the same time.

2. OBSERVATIONS AND ANALYSIS

We observed Sco X-1 with the *Rossi X-Ray Timing Explorer* PCA (Bradt, Rothschild, & Swank 1993) 20 times during 1996 May 24–28. Each observation consisted of 2–4 continuous data intervals of 1–3 ks each. Single- and double-event data (Paper I) were recorded in parallel and combined off-line to enhance sensitivity. A time resolution of 1/8192 s (~0.125 ms) was used throughout.

During these observations, various offset angles were used,

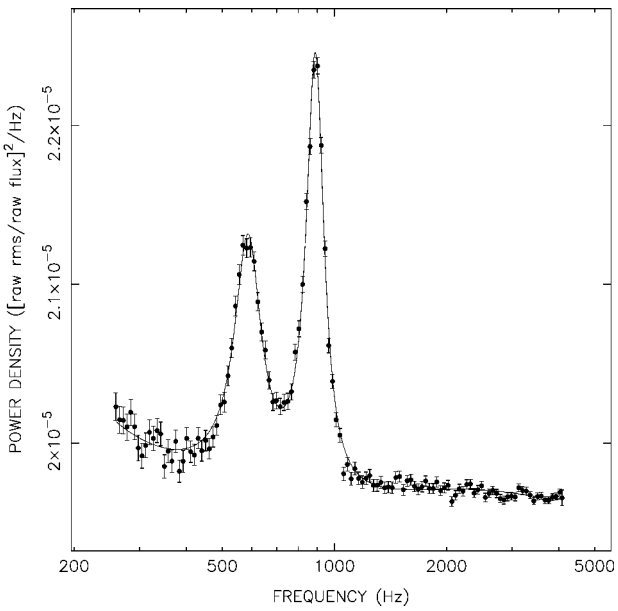

FIG. 1.—Power spectrum from ~10 ks of data showing double kilohertz QPO peaks, with best fit superimposed. Note the absence of additional peaks. The sloping continuum above 1 kHz is instrumental (§ 2).

and all five detectors were not always on. For these reasons, the expected *Z*-track in the X-ray color-color diagram cannot be recovered now; this awaits better understanding of the spectral calibration of the PCA at high count rates and off-axis source positions. Raw count rates varied between 60 and 1.3×10^5 counts s^{-1} (2–60 keV).

We calculated power spectra of all 0.125 ms data using 16 s data segments, and we calculated one average spectrum for each continuous data interval. For measuring the properties of the kilohertz QPO, we fitted the 256–4096 Hz power spectra (Fig. 1) with a function consisting of a constant, two Lorentzian peaks, and either a broad sinc function or a broad sinusoid to represent the dead-time–modified Poisson noise, depending on the Very Large Event window setting (Zhang et al. 1995; Zhang 1995). The PCA dead-time process at 10^5 counts s^{-1} is not, as yet, sufficiently well understood to predict this Poisson component accurately. Therefore, we cannot report on the properties of any intrinsic broad noise components in the kilohertz range.

For measuring the 45 Hz QPO and its harmonic, we fitted the 16–256 Hz power spectra with a broad Lorentzian centered near zero frequency to represent the continuum, and one or two Lorentzian peaks to model the QPO. The conversion of the power in the QPO peaks to fractional rms amplitude depends on the derivative of the dead-time transmission function with respect to count rate (van der Klis 1989), which we do not know. The dead time is expected to suppress the QPO amplitude more than the total count rate. Our reported raw (i.e., uncorrected for dead time) fractional rms amplitudes are therefore lower limits to the true values. These could be several times as large.

3. RESULTS

Kilohertz QPOs were detected in all observations. The peaks (Fig. 1) are very significant, with raw rms values of up to 2.5%, and the spectra are well fitted by the fit function described in § 2. Figure 2 illustrates the changes in power-

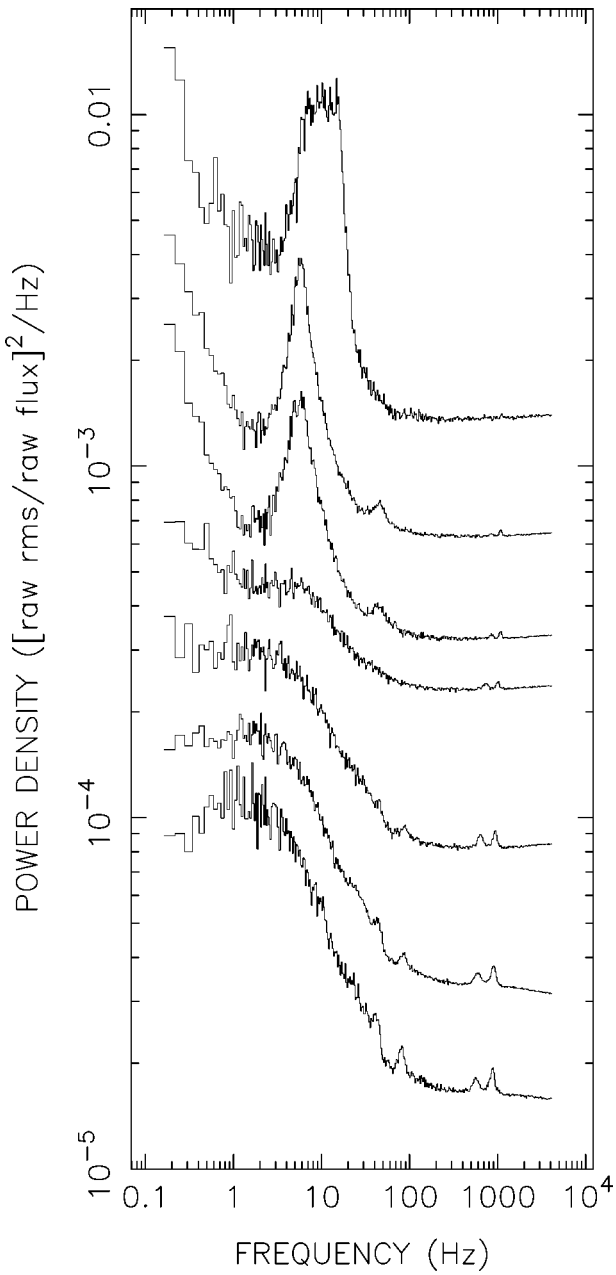

FIG. 2.—Representative ~3 ks power spectra sorted according to inferred $\dot{M}$ (increasing upward) and shifted up by factors of 1, 2, 5, 10, 20, 40, and 80, respectively, for clarity. The frequency of the upper kilohertz peak increases with $\dot{M}$ from 872 to 1115 Hz, that of the lower one from 565 to 890 Hz. The large width of the 10 Hz peak in the top trace is due to peak motion. The sloping continua in the kilohertz range are instrumental (§ 2).

spectral shape as a function of inferred $\dot{M}$. Notice the increase in frequency and the decrease in power of the two kilohertz QPO peaks, the emergence of the normal-branch oscillations (NBOs) near 6 Hz apparently *from* the low-frequency noise (LFN), and the complicated variations in strength and shape of the 45 and 90 Hz peaks with $\dot{M}$ (increasing upward). As in Paper I, the frequency of the NBOs is correlated to that of the kilohertz QPOs.

Since we cannot estimate $\dot{M}$ from the X-ray color-color diagram, we plot in Figure 3 the results of our fits versus the centroid frequency ν_u of the upper peak; ν_u increases mono-

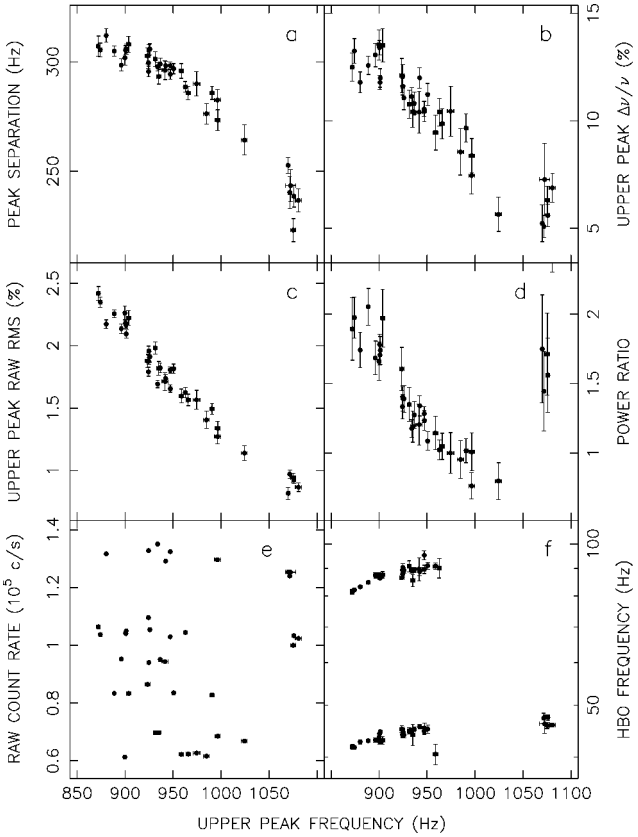

FIG. 3.—(*a*) Kilohertz peak separation, (*b*) relative width (FWHM divided by centroid frequency, expressed in percent, and (*c*) raw fractional rms amplitude of the highest frequency ("upper") peak; (*d*) ratio of the power in the upper to that in the lower peak, (*e*) raw count rate, and (*f*) HBO first and second harmonics' frequency as a function of the frequency of the upper kilohertz peak. One data point at 1075 Hz with a value near 3 is off-scale in (*d*). Eight low signal-to-noise ratio data points were not plotted. The gap between 1000 and 1075 Hz is due to a lack of good data.

tonically with position along the *Z*-track and, by inference, $\dot{M}$ (Paper I). Inspection of the variations in the properties of the NBOs, whose relation to $\dot{M}$ is known, confirms this.

Figure 3*a* shows the variation of the kilohertz peak separation. There is a strong decrease with ν_u: when their frequencies increase, the two peaks move closer together systematically. The relation of peak separation to ν_u appears to be nonlinear. Figure 3*b* shows that the higher frequency QPOs become more coherent as their frequency increases. The same trend is present, although less pronounced, in the lower frequency QPOs. The ratio of upper to lower kilohertz-peak width (not shown) is roughly constant at 1. Figure 3*c* shows how the raw fractional rms amplitude of the upper peak falls with $\dot{M}$. Again, the lower peak shows a similar trend, but less pronounced. Although the raw rms values are dead time, and therefore count rate–dependent (§ 2), the changes in raw count rate are random (Fig. 3*e*), so that the trend in rms must be intrinsic to the source. Figure 3*d* shows the kilohertz peaks' power ratio (which is essentially free of dead-time effects, since any timescale dependence in these effects is expected to become appreciable only for timescales near the dead time, ~10 μs; Zhang 1995). The power ratio varies nonmonotonically as a function of ν_u, dropping by more than a factor of 2 between 875 and 1000 Hz, then increasing again.

We detect no other kilohertz QPO peaks. When $\nu_u < 1$ kHz and the detected peaks are relatively strong, any other kilohertz peaks of similar width are typically less than 0.025–0.2 times the power in the detected peaks (95% confidence), depending on data selection. For $\nu_u > 1$ kHz, these limits worsen as the detected peaks get weaker.

Finally, Figure 3*f* shows the frequencies of the ~45 and ~90 Hz peaks. For $\nu_u < 960$ Hz, the 45 Hz peak has a width of ~8 Hz, and the 90 Hz peak of 20–40 Hz. Both peaks drop rapidly in raw rms amplitude as ν_u increases, from ~1% at $\nu_u \sim 850$ to below the detection limit of ~0.4% between 960 and 1000 Hz. There are no good data between 1000 and 1075 Hz. At 1075 Hz, the ~45 Hz peak reappears at 1% rms, now much broader (20–40 Hz; see also Fig. 2).

4. DISCUSSION

Our data place severe constraints on any model for kilohertz QPOs discussed so far. We note that the twin kilohertz QPOs in Sco X-1, and those in the atoll sources, are likely to be the same phenomenon. The frequencies, their dependence on $\dot{M}$, the coherencies, the peak separations, and the fact that there are *two* peaks, one of which sometimes becomes undetectable at extreme $\dot{M}$, are too similar to be attributed to just coincidence. Even the amplitude of the kilohertz QPOs in Sco X-1 is in the range of that seen in the atoll sources (although, in some of them, much higher values have been seen). This implies then that the variable peak separation we detect in Sco X-1 must be explained within the same model as the properties of the twin peaks in atoll sources.

The 45 and 90 Hz QPOs we reported here are nearly certainly the first and second harmonic of the horizontal-branch QPO (HBO), usually seen in *Z*-sources in the horizontal and upper normal branches (see van der Klis 1995). This was already tentatively suggested for the broad 45 Hz peak seen when $\nu_u > 1075$ Hz in Paper I. The similarities with HBOs in other *Z*-sources include the frequency, its increase (but see Wijnands et al. 1996a), and the decrease in rms, with $\dot{M}$, and the presence of a second harmonic. This constitutes the first positive identification of HBOs in Sco X-1.

The morphology of the spectra in Figure 2 seems to suggest that the well-known, slightly peaked broad noise component below 20 Hz, usually called low-frequency noise, "peaks up" into the also well-known 6 Hz normal branch QPO (NBO) when $\dot{M}$ increases. Appearances may deceive. One way to check whether this suggested relation between NBO and LFN is real would be to study the photon energy dependence of the amplitude and phase of the variability, which in NBOs can be quite characteristic (Mitsuda & Dotani 1989). There is a small shoulder in our spectra below the 45 Hz peak (see, e.g., Fig. 2, second spectrum from below) that can be identified perhaps as the true signature of the noise component that is expected to accompany HBOs (cf. Lamb et al. 1985).

The photon bubble model (Klein et al. 1996), and also some neutron star vibration models, predict several kilohertz QPO peaks at frequencies above those of the two detected ones, and of similar strength as these. The fact that we observe just these two kilohertz peaks, with good upper limits on any additional ones, is a strong argument against these models.

If the kilohertz QPOs are due to a millisecond X-ray pulsar whose pulsations we see (Doppler-shifted) reflected off inhomogeneities in the Fortner, Lamb, & Miller (1989) radial flow (Paper I), then one would expect the QPOs to become weaker at low $\dot{M}$, when the radial flow subsides; instead we find that the

kilohertz QPOs become much stronger at low $\dot{M}$. In a variant on this model, let us suppose that two relativistic jets are emerging in opposite directions from near the neutron star, and that we are seeing the signal from a central millisecond X-ray pulsar, not directly, but reflected off inhomogeneities in the jets. Because there are two jets, there are two QPO peaks, at $\nu_{\mp} = \nu_{\rm pulse}(1 - v/c)/[1 \pm (v/c)\cos\theta]$, where v is the jets' speed, θ their angle with the line of sight, and $\nu_{\rm pulse}$ the unseen pulse frequency (van der Klis 1996). Such a model fits very well to the nonlinear relation plotted in Figure 3 *a*, with $\nu_{\rm pulse} = 1370$ Hz (which could be twice the spin rate of the neutron star) and $\theta = 61°$, if v/c decreases from 0.48 to 0.26 with increasing $\dot{M}$. The model predicts that the X-ray spectra from the two QPO peaks should show similarly different redshifts as the QPO frequencies. However, this kinematic model has no way to account for the constant peak separations over a large range in QPO frequency reported in atoll sources.

In view of the observations of three commensurate frequencies in several atoll sources (§ 1), beat-frequency models (BFMs) are the mechanism of choice for explaining kilohertz QPOs. The fact that in Sco X-1 (this Letter), GX 5−1 (van der Klis et al. 1996c), and GX 17+2 (van der Klis et al. 1997) we observe HBOs and kilohertz QPOs simultaneously shows conclusively that *both* cannot be explained by the magnetospheric BFM. If this mechanism produces the HBOs (§ 1), then the kilohertz QPOs need another model.

Beat-frequency models with the neutron star spin as one of the participating frequencies predict a constant kilohertz-peak separation, which was consistent with observations so far. However, this prediction is clearly contradicted by our Sco X-1 data. In order to explain the data, such BFMs would have to be modified such that, in addition to the unseen (in Sco X-1) spin frequency ν_s, there is *another* unseen frequency beating with ν_s to produce one of the two kilohertz peaks. The sonic-point beat-frequency model (Miller et al. 1997) may allow such modification (F. K. Lamb 1996, private communication). If this model explains the kilohertz QPOs, and the magnetospheric beat-frequency model the HBOs, then in Sco X-1 the sonic radius is approximately $[\nu_u/(\nu_{\rm HBO} + \nu_s)]^{-2/3} \sim 0.5$ times the magnetospheric radius, implying the presence of a considerable near-Keplerian flow, where clumps remain in stable orbit for up to 10^2 cycles, well within the magnetosphere.

This work was supported in part by the Netherlands Organization for Scientific Research (NWO) under grant PGS 78-277, and by the Netherlands Foundation for Research in Astronomy (ASTRON) under grant 781-76-017. We gratefully acknowledge useful comments on the manuscript by Stefan Dieters, Erik Kuulkers, Jan van Paradijs, and Walter H. G. Lewin.

REFERENCES

Alpar, M. A., & Shaham, J. 1985, Nature, 316, 239
Berger, M., et al. 1996, ApJ, 469, L13
Bradt, H. V., Rothschild, R. E., & Swank, J. H. 1993, A&AS, 97, 355
Ford, E., et al. 1997, ApJ, 475, L123
Fortner, B. F., Lamb, F. K., & Miller, G. S. 1989, Nature, 342, 775.
Hasinger, G., & van der Klis, M. 1989, A&A, 225, 79
Klein, R. L., Jernigan, G. J., Arons, J., Morgan, E. H., & Zhang, W. 1996, ApJ, 469, L119
Lamb, F. K., Shibazaki, N., Alpar, M. A., & Shaham, J. 1985, Nature, 317, 681
Miller, M. C., Lamb, F. K., & Psaltis, D. 1997, ApJ, submitted
Mitsuda, K., & Dotani, T. 1989, PASJ, 41, 557
Morgan, E. H., & Smith, D. A. 1996, IAU Circ. 6437
Smale, A. P., Zhang, W., & White, N. E. 1996, IAU Circ. 6507
Strohmayer, T., Lee, U., & Jahoda, K. 1996a, IAU Circ. 6494
Strohmayer, T., Zhang, W., Smale, A., Day, C., Swank, J., Titarchuk, L., & Lee, U. 1996b, ApJ, 469, L9
van der Klis, M. 1989, in NATO ASI Conf. 262, Timing Neutron Stars, ed. H. Ögelman & E. P. J. van den Heuvel (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. 1996, in IAU Colloq. 163, Accretion Phenomena and Related Outflows, ed. D. Wickramasinghe, L. Ferrario, & G. Bicknell (San Francisco: ASP) in press
van der Klis, M., et al. 1997, IAU Circ. 6565
van der Klis, M., Swank, J. H., Zhang, W., Jahoda, K., Morgan, E. H., Lewin, W. H. G., Vaughan, B., & van Paradijs, J. 1996a, ApJ, 469, L1 (Paper I)
van der Klis, M., et al. 1996b, IAU Circ. 6424
———. 1996c, IAU Circ. 6511
Wijnands R., & van der Klis, M. 1997, ApJL, in press
Wijnands, R. A. D., van der Klis, M., Psaltis, D., Lamb, F. K., Kuulkers, E., Dieters, S., van Paradijs, J., & Lewin, W. H. G. 1996a, ApJ, 469, L5
Wijnands, R. A. D., van Paradijs, J., Lewin, W. H. G., Lamb, F. K., Vaughan, B., Kuulkers, E., & Augusteijn, T. 1996b, IAU Circ. 6447
Zhang, W. 1995, *XTE*/PCA Internal Memo.
Zhang, W., Jahoda, K., Swank, J. H., Morgan, E. H., & Giles, A. B. 1995, ApJ, 449, 930
Zhang, W., Lapidus, I., Swank, J. H., White, N. E., & Titarchuk, L. 1997, IAU Circ. 6541
Zhang, W., Lapidus, I., White, N. E., & Titarchuk, L. 1996, ApJ, 469, L17

Note added in proof.—Further photon bubble model calculations have now produced power spectra that more nearly resemble the observed ones (R. L. Klein 1997, private communication).