We report the results of a search for burst oscillations during thermonuclear X-ray bursts from the low-mass X-ray binary EXO 0748–676. With the proportional counter array on board the Rossi X-Ray Timing Explorer (RXTE), we detected a 45 Hz oscillation in the average power spectrum of 38 thermonuclear X-ray bursts from this source. We computed power spectra with 1 Hz frequency resolution for both the rising and decaying portions of 38 X-ray bursts from the public RXTE archive. We averaged the 1 Hz power spectra and detected a significant signal at 45 Hz in the decaying phases of the bursts. The signal is detected at a significance level of $4 \times 10^{-8}$. No similar signal was detected in the rising intervals. A fit to the oscillation peak at 0.25 Hz resolution gives a frequency of $\nu_p = 44.7 \pm 0.06$ Hz and an oscillation quality factor of $Q = \nu_p/\Delta\nu_{\text{FWHM}} = 80 \pm 18$. The average signal amplitude is $\approx 3\%$ (rms). The detection of 45 Hz burst oscillations from EXO 0748–676 provides compelling evidence that this is the neutron star spin frequency in this system. We use the inferred spin frequency to model the widths of absorption lines from the neutron star surface and show that the widths of the absorption lines from EXO 0748–676 recently reported by Cottam et al. are consistent with a 45 Hz spin frequency as long as the neutron star radius is in the range from about 9.5 to 15 km. With a known spin frequency, precise modeling of the line profiles from EXO 0748–676 holds great promise for constraining the dense matter equation of state.

**Subject headings:** binaries: general — stars: individual (EXO 0748–676) — stars: neutron — stars: rotation — X-rays: bursts — X-rays: stars

1. INTRODUCTION

High time resolution observations of thermonuclear X-ray bursts with the Rossi X-Ray Timing Explorer (RXTE) have now found X-ray brightness oscillations, or burst oscillations, from more than a dozen low-mass X-ray binaries (LMXBs). A large body of evidence supports the conclusion that such oscillations are produced by spin modulation of the X-ray burst flux (for a recent review, see Strohmayer & Bildsten 2004 and references therein). In the last 2 years, the detection of burst oscillations at the known spin frequencies of two accreting millisecond pulsars, SAX J1808.4–3658 (Chakrabarty et al. 2003) and XTE J1814–338 (Strohmayer et al. 2003), has provided particularly strong confirmation of the spin modulation hypothesis.

EXO 0748–676 (hereafter EXO 0748) is a well-studied LMXB discovered by EXOSAT in 1985 (Parmar et al. 1985). This transient X-ray burst source exhibits irregular X-ray dips and periodic eclipses (Gottwald et al. 1986). Timing of the eclipses revealed a 3.82 hr orbital period (Parmar et al. 1986; Hertz et al. 1996; Wolff et al. 2002). Based on the eclipse duration and orbital period, the system inclination angle is constrained to be in the range $75^\circ$–$82^\circ$ (Parmar et al. 1986), which depends on assumptions about the neutron star’s companion. X-ray timing studies of the source have revealed the presence of $\approx 1$ Hz quasi-periodic oscillations (QPOs) as well as a single kilohertz QPO, which is presumably the lower kilohertz peak of a pair (Homan et al. 1999; Homan & van der Klis 2000). Homan & van der Klis (2000) searched a total of 10 X-ray bursts from EXO 0748 for burst oscillations. They searched the 100–1000 Hz frequency band (with 2 Hz resolution) but found no significant signals. They placed upper limits on the amplitude of oscillations to be between 4% and 11% (rms) during the rise of the bursts in the 2–60 keV band.

EXO 0748 is one of a few neutron star LMXBs for which high-resolution spectroscopic observations have been obtained for a large number of X-ray bursts. Cottam et al. (2002) reported the presence of narrow absorption lines in a study of EXO 0748 burst spectra observed with the Reflection Grating Spectrometer (RGS) on XMM-Newton. Using co-added data from 28 bursts, they found evidence for absorption features between 13 and 14 Å, which they interpreted as redshifted absorption lines of the $n = 2$–$3$ transitions from hydrogen-like Fe. Their line identifications imply a neutron star surface redshift of $z = 0.35$. Here $1 + z = (1 - 2GM/c^2R)^{-1/2}$, where $M$ and $R$ are the neutron star mass and radius, respectively. A measurement of $z$ fixes the mass to radius ratio, or the compactness, but additional information is required to determine both the mass and radius separately.

A measurement of the neutron star spin frequency in EXO 0748 could provide the additional information required to measure both its mass and radius. This is possible because the observed width of surface spectral lines provides information about the surface rotational velocity, $v_{\text{rot}}$, and thus the stellar radius if the spin frequency, $\nu_{\text{spin}}$, is known, viz., $v_{\text{rot}} \propto \nu_{\text{spin}}R$. Even at modest rotation rates, it is expected that rotational Doppler broadening will dominate over thermal Doppler and Stark broadening (see Bildsten et al. 2003). Rotational broadening depends on the surface rotational velocity, $v_{\text{rot}} = 2\pi \nu_{\text{spin}}R \sin i$, where $i$ is the system inclination (assuming the rotation axis is perpendicular to the orbital plane). Since the inclination of EXO 0748 is tightly constrained by the presence of eclipses, a measurement of the stellar radius would, in principle, be possible if the spin frequency were known. A radius determination, combined with $z$, would then allow for a constraint to be placed on the mass. Until now,
We began by searching the public data archive and found 38 X-ray bursts from EXO 0748 in the 1–2048 Hz band. The frequency bins are 1 Hz, and the Nyquist frequency is 2048 Hz. Note the prominent peak at ≈45 Hz. The increase in power toward low frequencies is due to the decrease in count rate with time during the burst decays. A characteristic error bar is also shown.

Since oscillation searches in individual bursts from EXO 0748 have been unsuccessful, we elected to search by “stacking” (averaging) the power spectra from all available bursts. We investigated the implications of this finding for the widths of absorption lines from the neutron star surface. In order to quantify the significance of this peak, we need to understand the noise power distribution of our power spectrum. One each for the rises and decays of the burst profiles. We selected rising intervals from just prior to burst onset to near the burst peak. We started the decay intervals at the end of the rise intervals and stopped when the count rate had fallen to about 5% of the peak rate (above the preburst level). For both the rises and decays, we “rounded off” the intervals so that the length of each was an even multiple of the shortest length. Because we have bursts of differing length, this allowed us to linearly rebin the power spectra of each burst to the same frequency resolution before averaging. This procedure resulted in rise intervals lasting 5 or 10 s and decay intervals from 16 to 256 s, with most being 64 or 128 s.

In this Letter, we report the discovery of 45 Hz burst oscillations from EXO 0748 with the proportional counter array (PCA) on board RXTE. We investigate the implications of this finding for the widths of absorption lines from the neutron star surface. In § 2, we summarize our search and detection of a 45 Hz burst oscillation signal in the average power spectrum of the decay phases of 38 bursts from EXO 0748. In § 3, we show that the width of the lines observed from EXO 0748 with the RGS are consistent with a 45 Hz spin frequency if the neutron star radius is 9.5–15 km. We conclude in § 4 with a brief summary of our results.

2. OBSERVATIONS AND DATA ANALYSIS

Since oscillation searches in individual bursts from EXO 0748 have been unsuccessful, we elected to search by “stacking” (averaging) the power spectra from all available bursts. We began by searching the public RXTE data archive and found a total of 38 type I X-ray bursts from EXO 0748. All the bursts were observed (between 1996 August 15 and 2003 February 19) with the PCA, and high time resolution event mode data were available. For the purposes of computing power spectra, we used light curves sampled at 4096 Hz, yielding a Nyquist frequency of 2048 Hz. Since burst oscillation amplitudes generally increase with photon energy (see Strohmayer et al. 1997; Muno et al. 2003), we computed power spectra in the energy band 6–60 keV. All power spectra were normalized such that a pure Poisson noise process would be flat with a mean of 2 (see Leahy et al. 1983).

From the sample of 38 bursts, we computed two average power spectra; one each for the rises and decays of the burst profiles. We selected rising intervals from just prior to burst onset to near the burst peak. We started the decay intervals at the end of the rise intervals and stopped when the count rate had fallen to about 5% of the peak rate (above the preburst level). For both the rises and decays, we “rounded off” the intervals so that the length of each was an even multiple of the shortest length. Because we have bursts of differing length, this allowed us to linearly rebin the power spectra of each burst to the same frequency resolution before averaging. This procedure resulted in rise intervals lasting 5 or 10 s and decay intervals from 16 to 256 s, with most being 64 or 128 s.

Since burst oscillations can drift in frequency by an order of 1–2 Hz, we rebinned each individual burst power spectrum to 1 Hz resolution and then averaged the 1 Hz power spectra of all the bursts (rises and decays separately). We estimated the errors on the individual burst power spectra using the statistical error associated with rebinning (averaging) $N_i$-independent powers for the $i$th burst, viz., $\sigma_i = 2/\sqrt{N_i}$. We then propagated these uncertainties to estimate the errors for the averaged spectra. Figure 1 shows the average power spectrum computed from the decaying portion of the bursts in the 1–2048 Hz band. This spectrum contains a prominent peak at ≈45 Hz. The increase in mean power below about 20 Hz is not unexpected, since, by definition, the decay light curves are all trending down in count rate.

In order to quantify the significance of this peak, we need to understand the noise power distribution of our power spectrum. First, we fitted the continuum power level from 20 to 2048 Hz with a constant $+$ power-law model, excluding the 45 Hz peak to avoid biasing the fit to higher values. We then rescaled our power spectrum by dividing by the best-fitting continuum model. Figure 2 shows the power spectrum and best-fitting continuum model (top) along with the rescaled spectrum (bottom). To estimate the noise power distribution, we computed a histogram of the number of noise powers with power between $p_i$ and $p_i + \Delta p$, using $\Delta p = 0.01$. Figure 3 shows the resulting noise
power histogram and best-fitting $\chi^2$ distribution (solid line). A $\chi^2$ distribution with a mean of 2 and 3446 degrees of freedom fits extremely well. This distribution is, to high accuracy, a Gaussian with a mean of 2.000 ± 0.0011 and a standard deviation, $\sigma$, of 3.0481 ± 0.0008. It is not unexpected that the distribution is effectively Gaussian, especially given the large number of independent powers averaged (van der Klis 1989).

We now estimate the significance of the 45 Hz peak using the fitted $\chi^2$ distribution. The 45 Hz peak has a power value of 2.3352 compared in Figure 4. The power spectrum from the first half (top) shows a strong peak at 45 Hz, while no signal is detected in the other (faider) half. This demonstrates that the 45 Hz signal is associated with the brighter portions of the burst decay profiles, as is typical for burst oscillations in other sources. As an additional test of robustness, we divided the burst sample into two sets (each with 19 bursts) and computed average power spectra for each set. We detected the 45 Hz peak in both sets.

3. SPIN FREQUENCY AND LINE PROFILES

We have detected an oscillation signal at 45 Hz during X-ray bursts from EXO 0748. The frequency width of the signal and its clear association with the X-ray bursts (see Fig. 4) indicates that it is most likely a burst oscillation signal similar to those seen in more than a dozen other LMXBs, therefore establishing a spin frequency of 45 Hz for the neutron star in EXO 0748. Interestingly, this is the slowest spin period yet measured for a burst oscillation source. This begs the question, why is the spin frequency so much lower in EXO 0748 compared to other LMXBs? One possibility is that the source is in spin equilibrium with a neutron star magnetic field that is stronger than in other LMXBs. Using typical estimates of the accretion torque (see, for example, Psaltis & Chakrabarty 1999), one would require a magnetic field in the range $B \approx (1.5-5) \times 10^6$ G, assuming a time-averaged mass accretion rate in the range $(0.01-0.1)\dot{m}_{\text{Edd}}$, where $\dot{m}_{\text{Edd}}$ is the Eddington accretion rate. Knowledge of the spin frequency also has implications for the kilohertz QPO frequencies expected from the system. Based on behavior from other sources (i.e., those with $\nu_{\text{spin}} < 400$ Hz), one would expect a frequency separation of 45 Hz for the kilohertz QPO pair. This would make a nice test case; however, the comparatively small frequency separation (comparable to the width of the lower kilohertz QPO in some systems) could make resolving both peaks difficult.

The detection of the spin frequency in EXO 0748 is very important given the evidence for narrow, gravitationally redshifted absorption lines from this object (Cottam et al. 2002). To investigate the consistency of the absorption line widths observed by Cottam et al. (2002) with a neutron star spin frequency of 45 Hz, we computed model line profiles from a rotating neutron star (see also Datta & Kapoor 1988; Özel & Psaltis 2003). Our modeling builds on that previously described by Nath et al. (2002) and is discussed in detail by Strohmayer (2004). Briefly, the model includes photon deflection in the Schwarzschild metric, relativistic beaming and aberration, and gravitational redshifts and allows for arbitrary viewing geometries. We assume the whole surface of the neutron star is involved in line formation and that the rotational axis is perpendicular to the orbit plane. We use an inclination of 78°. We model the intrinsic line shape as a Gaussian with a width (FWHM) fixed at the value due to Stark and thermal Doppler broadening estimated by Bildsten et al. (2003) for the Hα transition. Finally, we convolve the model line profile observed at infinity with an RGS response model appropriate for the 13–14 Å band.

A detailed model fit to the RGS absorption-line data is be-
For both lines, a value of $\Delta \lambda / \lambda_{\text{FWHM}} = 0.018 \pm 0.004$. Figure 5 shows absorption-line profiles for a neutron star spinning at 45 Hz with different radii. As expected, larger neutron stars produce broader absorption lines, and even at 45 Hz the spin Doppler broadening dominates. At the half-intensity value of each line profile in Figure 5 is a horizontal line. The thin part of each line represents the maximum absorption line width, while the thick part denotes the minimum line width (both at $1 \sigma$). The vertical dotted lines denote the best-fit value of $\Delta \lambda / \lambda_{\text{FWHM}} = 0.018$. One can see from Figure 5 that radii in the range 9.5 km $< R < 15$ km (or, assuming $z$ is known, masses in the range $1.5 M_\odot < M < 2.3 M_\odot$) are consistent with the derived line widths and that the observed lines are best matched with $R \approx 11.5$ km ($M \approx 1.8 M_\odot$).

This comparison demonstrates that the observed line widths are consistent with a 45 Hz neutron star spin frequency and a reasonable range of neutron star radii. It also shows that precise measurements of the absorption line widths can, in principle, lead to an accurate measurement of the stellar radius. We will attempt to derive more precise radius constraints from detailed model fitting in future work.

### 4. SUMMARY

Our discovery of burst oscillations from EXO 0748–676 has established a spin frequency of 45 Hz for the accreting neutron star in this system. We have also shown that the observed widths of the absorption lines claimed by Cottam et al. (2002) to be gravitationally redshifted from the neutron star surface are consistent with such a spin frequency and with reasonable neutron star radii. This provides at least indirect support for the idea that the absorption lines could indeed come from the neutron star surface (i.e., they are not too narrow).

Finally, we have shown that detailed modeling of absorption-line profiles combined with spin measurements will likely provide a means to accurately measure both the masses and radii of neutron stars and thus tightly constrain the dense matter EOS.

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