Discovery of the Neutron Star Spin Frequency in EXO 0748–676

Adam R. Villarreal[1]

Department of Physics, University of Arizona, Tucson, AZ 85721; adamv@physics.arizona.edu

and

Tod E. Strohmayer

Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center, Greenbelt, MD 20771; stroh@milkyway.gsfc.nasa.gov

ABSTRACT

We report the results of a search for burst oscillations during thermonuclear X-ray bursts from the low mass X-ray binary (LMXB) EXO 0748–676. With the proportional counter array (PCA) onboard the *Rossi X-ray Timing Explorer* (RXTE) we have 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 4×10^{-8}. No similar signal was detected in the rising intervals. The oscillation peak is unresolved at 1 Hz frequency resolution, indicating an oscillation quality factor, $Q = \nu_0/\Delta\nu_{fwhm} > 45$, and 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 – 15 km. With a known spin frequency, precise modelling 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]NASA Harriet G. Jenkins Fellow

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 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 2003 and references therein). In the last two 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 low-mass X-ray binary (LMXB) first discovered by *EXOSAT* in 1985 (Parmar et al. 1985). This transient X-ray burst source exhibits both irregular X-ray dips and periodic eclipses (Gottwald et al. 1986). Timing of the eclipses has 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 from 75–82° (Parmar et al. 1986), where the spread 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 kHz peak of a pair (Homan et al. 1999; Homan & van der Klis 2000). Homan & van der Klis (2000) also 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 13–14 Å which they interpreted as redshifted absorption lines of the n = 2 to 3 transitions from hydrogen- and helium-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 ratio of mass to radius, 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 pin down both its mass and radius. This is possible because the observed width of surface spectral lines provides information about the surface rotational velocity, v_{rot}, and thus the stellar radius if the spin frequency, ν_{spin}, is known, viz. $v_{rot} \propto \nu_{spin} R$. Even at relatively modest rotation rates it is expected that rotational Doppler broadening will dominate over thermal Doppler and Stark broadening (see, for example, Bildsten, Chang & Paerels 2003). Rotational broadening depends on the maximum surface rotational velocity, $v_{rot} = 2\pi\nu_{spin} R \sin i$, 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 as well. Until now this has not been possible because burst oscillations and surface absorption lines have not been observed in the same source. Precise neutron star mass and radius measurements are crucial for understanding the equation of state (EOS) of supranuclear density matter (see, for example, Lattimer & Prakash 2001; Strohmayer 2004).

In this Letter we report the discovery of 45 Hz burst oscillations from EXO 0748 with the proportional counter array (PCA) onboard *RXTE*, and 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 between 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 previously 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 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, Ozel & Chakrabarty 2003), we computed power spectra in the energy band from about 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 countrate had fallen to about 5% of the peak rate (above the pre-burst 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 ranging from 16 to 256 s, with most being either 64 or 128 s.

Since burst oscillations are transient and can drift in frequency by order 1–2 Hz we rebinned each individual burst power spectrum to 1 Hz frequency 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 $i^{\rm th}$ burst, viz. $\sigma_i = 2/\sqrt(N_i)$. We then propagated these uncertainties in the standard way 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 $\approx$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 countrate.

In order to quantify the significance of this peak we must first understand the noise power distribution of our power spectrum. To begin, we fitted the continuum power level from 20–2048 Hz with a constant + power-law model. For this fit we excluded the 45 Hz peak, which would tend to bias the fit to slightly higher values. We then rescaled our power spectrum by dividing by the best fitting continuum model. Figure 2 shows the power spectrum and the best fitting continuum model (top) along with the rescaled spectrum (bottom). To estimate the noise power distribution we then computed a histogram of the number of noise powers with power levels between p_i and $p_i + \Delta p$ using $\Delta p = 0.01$. Figure 3 shows the resulting noise power histogram along with the best fitting χ^2 distribution (solid). A χ^2 distribution with a mean of 2 and 3,446 degrees of freedom fits extremely well. To high accuracy, this distribution is effectively a gaussian with a mean of 2.000 ± 0.0011 and a standard deviation of $\sigma = 0.0481 \pm 0.0008$. The fact that the distribution is effectively gaussian is not unexpected, especially given the large number of independent powers averaged (see van der Klis 1989).

We can now estimate the significance of the 45 Hz peak using the fitted χ^2 distribution. The 45 Hz peak has a power value of 2.335 (vertical dashed line in Figure 3), and the single trial probability of obtaining this value from the fitted distribution is 2.1×10^{-11}. Using a conservative number of trials of 2048 (the number of bins in our power spectrum), we arrive at a significance of 4.3×10^{-8}, which indicates a strong detection. The 45 Hz peak is unresolved at 1 Hz frequency resolution, indicating that the quality factor $Q = \nu_0/\Delta\nu_{fwhm} > 45$. This peak corresponds to an average signal amplitude of $\approx 3\%$ (rms).

To further investigate the association of the 45 Hz signal with the X-ray bursts from EXO 0748 we computed two additional power spectra in the same manner as before; one for the first half (ie. the brighter half) of the burst decay intervals and the other for the second half. These two power spectra are 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 (fainter) half. This demonstrates that the 45 Hz signal is indeed associated with the brighter portions of the burst decay profiles, as is typical for burst oscillations in other sources.

3. The 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 as well as its clear association with the X-ray bursts (see Figure 4) indicates that it is most likely a burst oscillation signal similar to those seen in more than a dozen other LMXBs, and therefore establishes 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 result is particularly exciting given the evidence for narrow, gravitationally redshifted absorption lines from this object (Cottam et al. 2002).

To investigate the consistency (or not) of the absorption line widths observed by Cottam et al. (2002) with a neutron star spin frequency of 45 Hz, we have computed model line profiles from a rotating neutron star. Our modelling builds on that previously described by Nath, Strohmayer & Swank (2002) and is described in more detail by Strohmayer (2004). Briefly, the model includes photon deflection in the Schwarzschild metric, relativistic beaming and aberration, gravitational redshifts, and allows for arbitrary viewing geometries. We assume that the whole surface of the neutron star is involved in the line formation, and we further assume that the rotational axis is perpendicular to the orbit plane. We use an inclination of 78.5°. 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, Chang & Paerels (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 $\AA$ band.

A detailed model fit to the RGS absorption line data is beyond the scope of this paper; however, we can compare the measured line width with our line broadening model and place some preliminary limits on the stellar radius. To do this we used the data from Cottam et al. (2002, see their Figure 1) to model the widths of the two absorption lines at 13 and

13.75 Å. We find, from a joint fit using gaussian profiles and only one width parameter for both lines, a value of $\Delta\lambda/\lambda_{fwhm} = 0.0176^{+0.0047}_{-0.0036}$. In Figure 5 we show a series of absorption line profiles for a neutron star spinning at 45 Hz with several 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 for each line profile in Figure 5 we placed a horizontal line. The thin portion of each line represents the maximum absorption line width, while the thick part denotes the minimum line width (both at 1σ). The vertical dotted lines denote the best-fit value of $\Delta\lambda/\lambda_{fwhm} = 0.0176$. One can see from Figure 5 that the range of radii shown ($9.5 < R < 15$) is approximately consistent with the derived line widths, and that the observed lines are best matched with $R \approx 11.5$ km.

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 lines 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 (ie. they are *not* too narrow). Finally, we have shown that detailed modelling 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.

REFERENCES

Barret, D., Olive, J. F., Boirin, L., Grindlay, J. E., Bloser, P. F., Chou, Y., Swank, J. H., & Smale, A. P. 1997, IAU Circ., 6793.

Bildsten, L., Chang, P., & Paerels, F. 2003, ApJ, 591, L29.

Chakrabarty, D., et al. 2003, Nature, 424, 42.

Cottam, J., Paerels, F., & Mendez, M. 2002, Nature, 420, 51.

Gottwald, M., Haberl, F., Parmar, A. N., & White, N. E. 1986, ApJ, 308, 213.

Homan, J., Jonker, P. G., Wijnands, R., van der Klis, M., & van Paradijs, J. 1999, ApJ, 516, L91.

Homan, J. & van der Klis, M. 2000, ApJ, 539, 847.

Lattimer, J. M. & Prakash, M. 2001, ApJ, 550, 426.

Leahy, D. A., et al. 1983, ApJ, 266, 160.

Marshall, F. E. & Markwardt, C. B. 1999, IAU Circ., 7103.

Muno, M. P., Ozel, F., & Chakrabarty, D. 2003, ApJ, 595, 1066.

Nath, N. R., Strohmayer, T. E., & Swank, J. H. 2002, ApJ, 564, 353.

Parmar, A. N., White, N. E., Giommi, P., & Gottwald, M. 1986, ApJ, 308, 199.

Parmar, A. N., White, N. E., Giommi, P., & Haberl, F. 1985, IAU Circ., 4039.

Strohmayer, T. E. 2004, in X-ray Timing 2003: Rossi and Beyond, ed. P. Kaaret, F. K. Lamb, & J. H. Swank, (AIP Conference Proceedings, Vol. 714), 245-252.

Strohmayer, T. E. & Bildsten, L. 2003, in Compact Stellar X-ray Sources, ed. W. H. G. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), in press (astro-ph/0301544).

Strohmayer, T. E., Markwardt, C. B., Swank, J. H., & in't Zand, J. J. M. 2003, ApJ, 597, L67.

Strohmayer, T. E. & Markwardt, C. B. 2002 ApJ, 577, 337.

Strohmayer, T. E., Jahoda, K., & Giles, A. B. 1997, ApJ, 486, 355.

van der Klis, M. 1989, in Timing Neutron Stars, ed. H. Ogelman & E. P. J. van den Heuvel, (Kluwer Academic Publishers), 27-69.

This preprint was prepared with the AAS LaTeX macros v5.0.

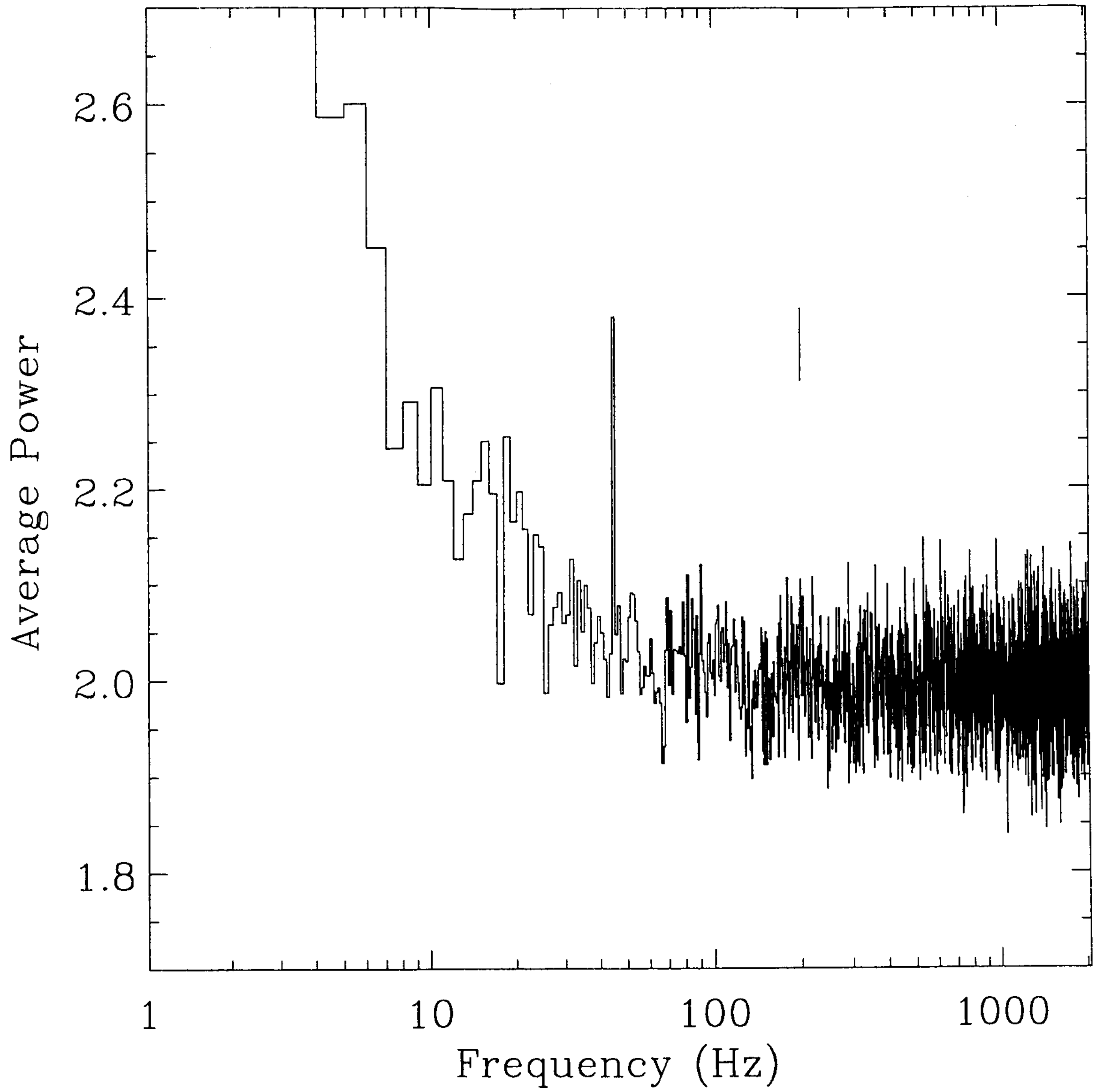

Figure 1: Average Leahy-normalized power spectrum of the decay intervals of 38 X-ray bursts from EXO 0748 in the 1–2048 Hz band. The frequency bins are 1 Hz and the Nyquist frequency is 2048 Hz. Note the prominent peak at $\approx$45 Hz. The increase in power towards low frequencies is due to the decrease in countrate with time during the burst decays. A characteristic error bar is also shown.

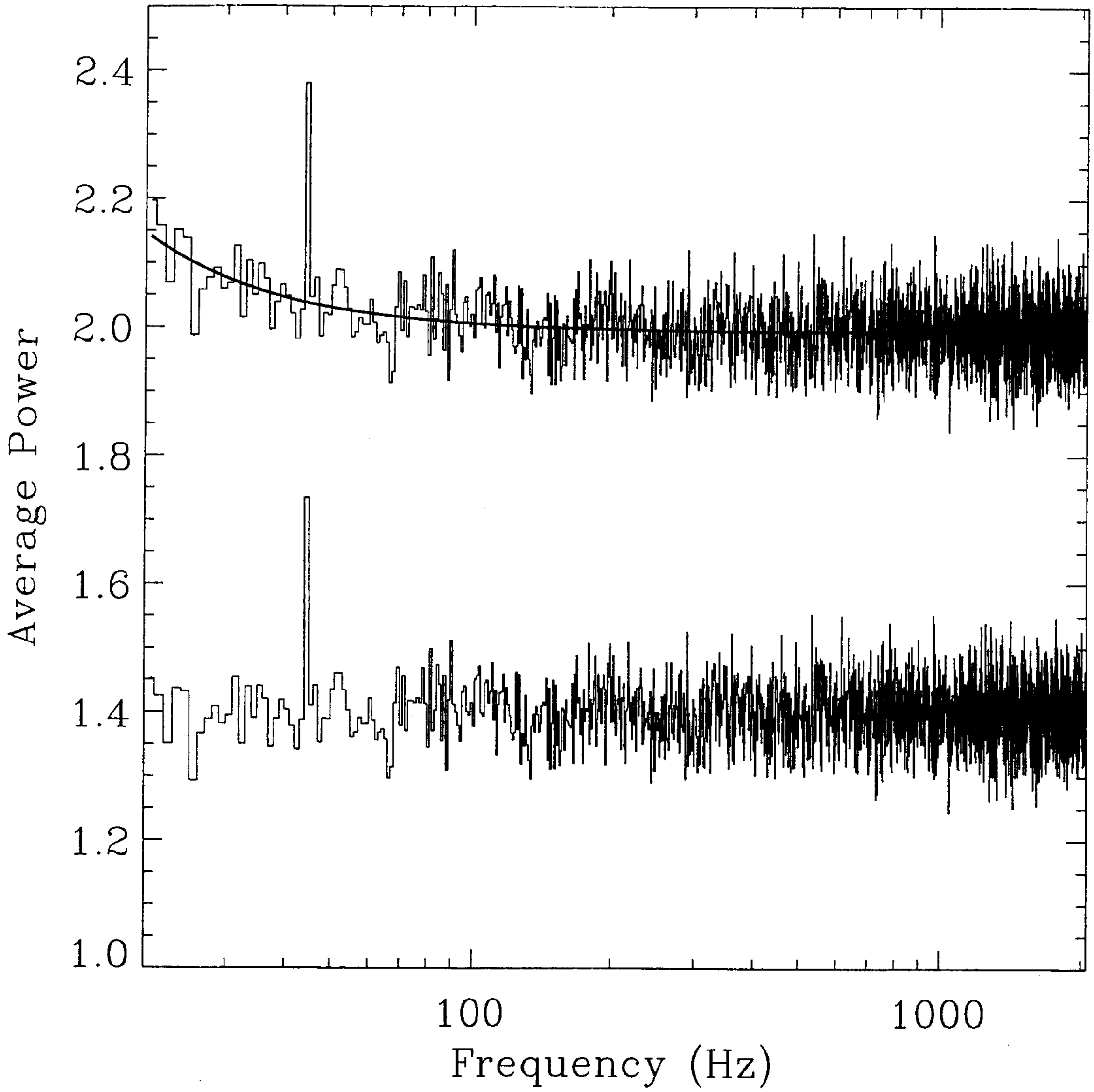

Figure 2: The same power spectrum from Figure 1 is shown in the 20–2048 Hz band along with the best fitting constant + power law model of the continuum (top). The renormalized power spectrum obtained by dividing by the continuum model (and multiplying by 2) is also shown (bottom). The renormalized spectrum has been displaced by −0.6 for clarity.

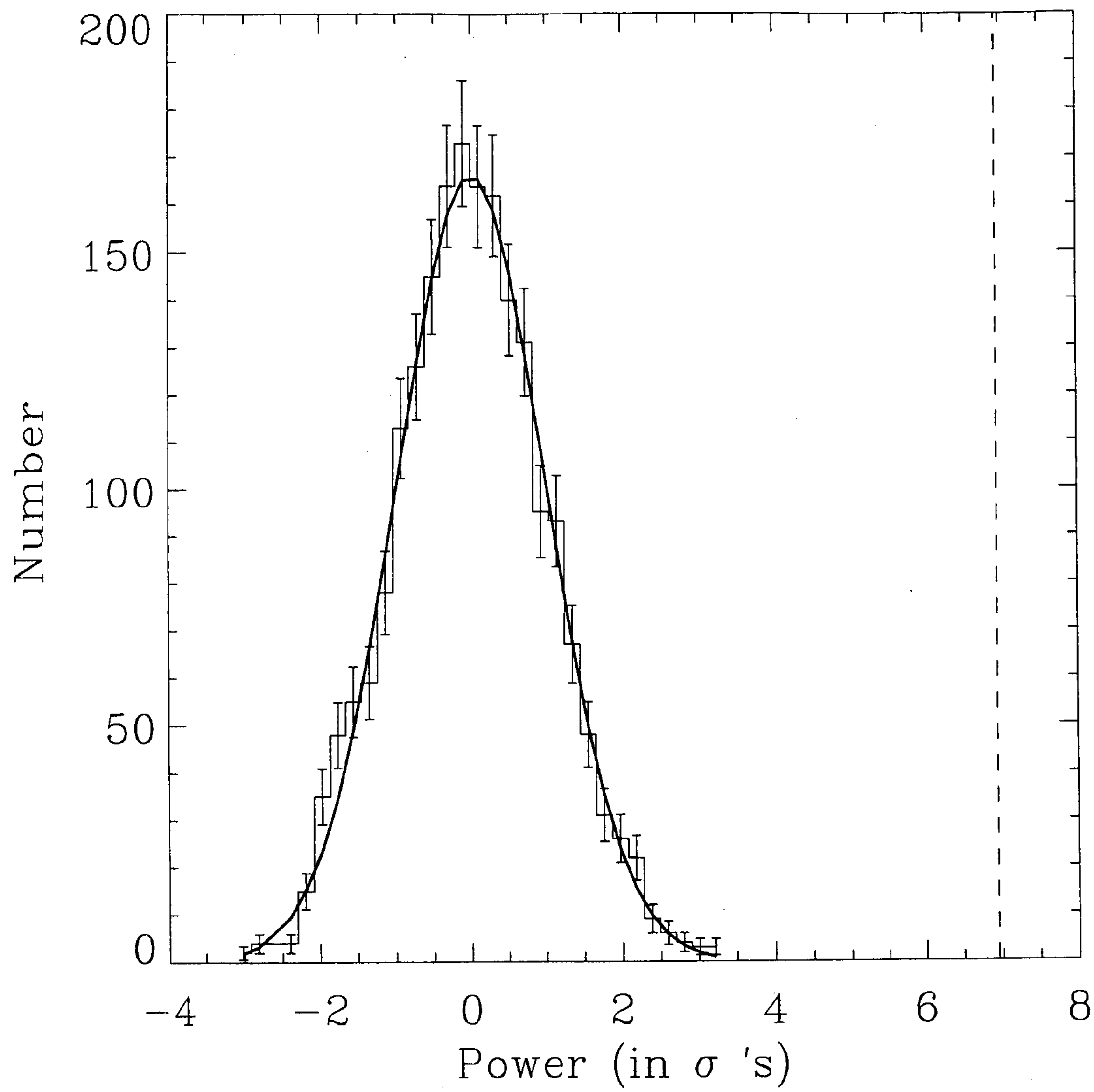

Figure 3: Distribution of noise powers for the average renormalized power spectrum shown in Figure 2 (histogram). The best fitting χ^2 model is also shown (solid). The distribution has been scaled to zero mean and the ordinate is in units of standard deviations (σ's). The power level of the 45 Hz peak is marked by the vertical dashed line and is $\approx 7\sigma$ from the mean.

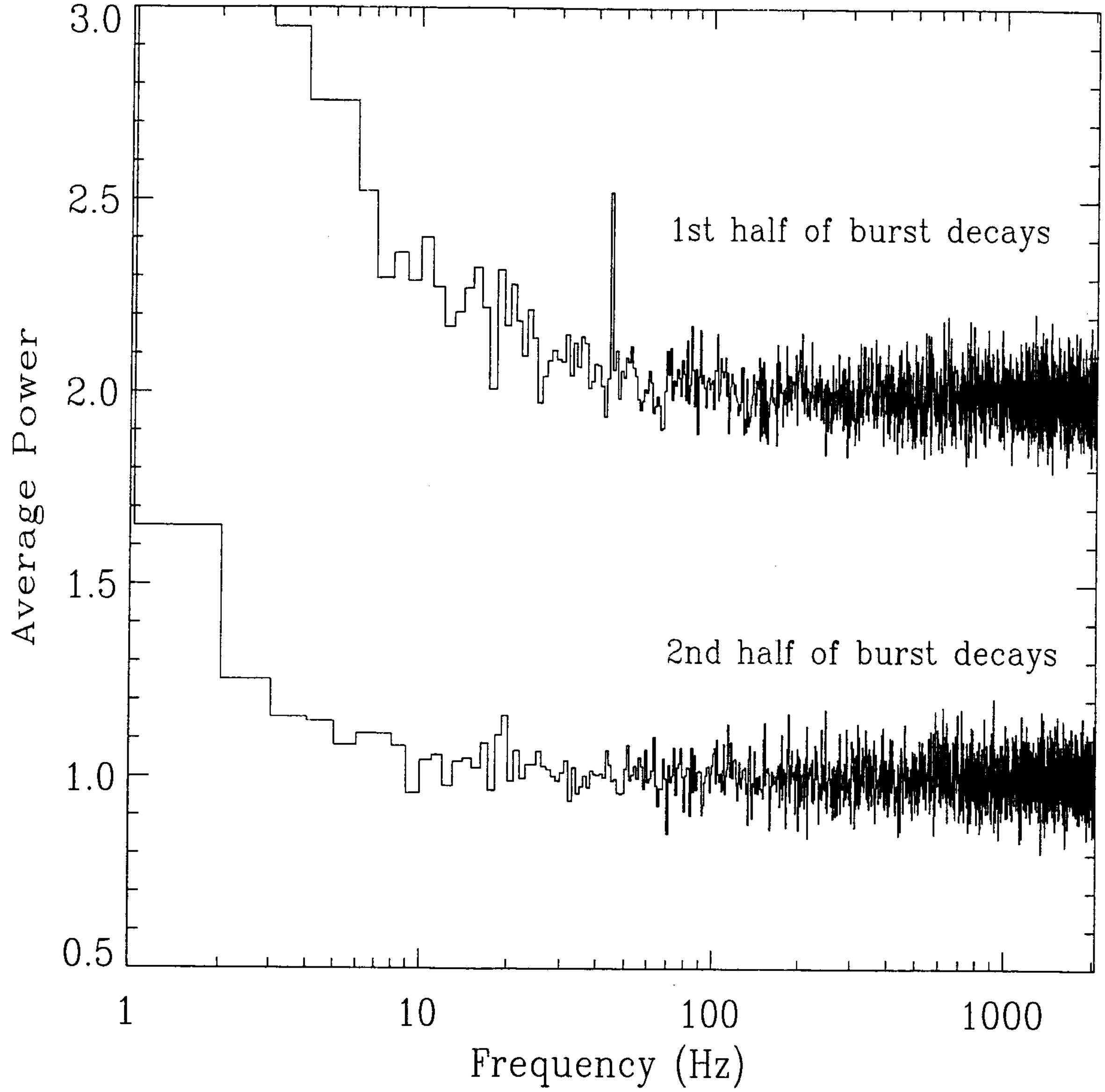

Figure 4: Comparison of average power spectra computed from the 1st half of the burst decay intervals (top) and the 2nd half (bottom). The 45 Hz signal is clearly associated with the 1st half of the decay intervals.

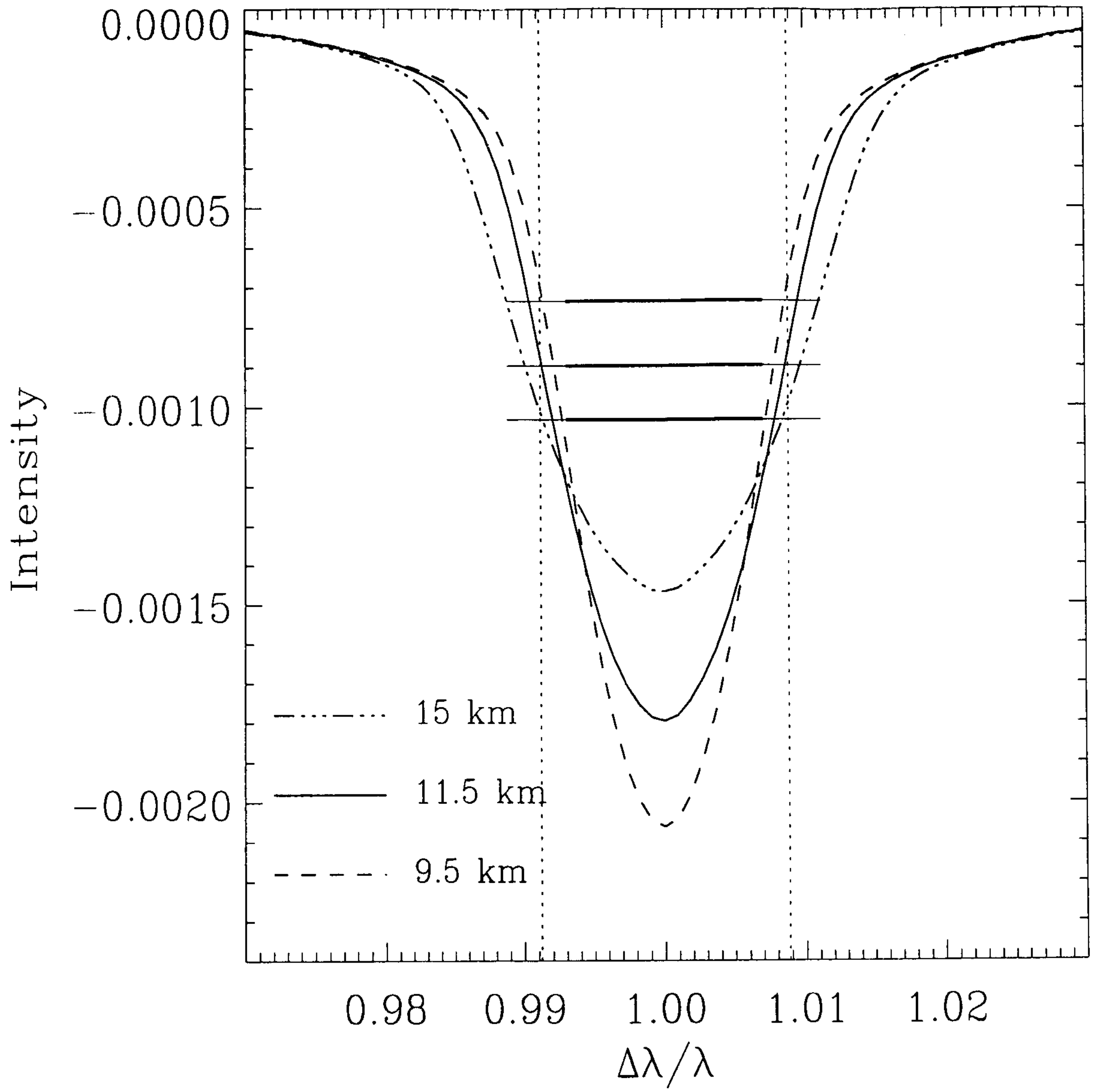

Figure 5: Model absorption line profiles from a neutron star rotating at 45 Hz for radii of 9.5 (dashed), 11.5 (solid) and 15 (dot-dashed) km. A horizontal line is located at the half-intensity point for each profile. The thin portion of each line represents the maximum width consistent with the RGS data from Cottam et al. (1σ), while the thick portion represents the minimum width (again, at 1σ). The vertical dotted lines denote the best-fit line width. Comparison of the model profiles and the measured line widths suggests $R = 11.5^{+3.5}_{-2.5}$. The model lines have been convolved with a line response function appropriate for the RGS at 13.5 $\AA$. This accounts for the shallow but broad wings of the profiles. See the text for more details and assumptions regarding the modelling.