Future Probes of the Neutron Star Equation of State Using X-ray Bursts

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Abstract.
Observations with NASA's Rossi X-ray Timing Explorer (RXTE) have resulted in the discovery of fast (200 - 600 Hz), coherent X-ray intensity oscillations (hereafter, "burst oscillations") during thermonuclear X-ray bursts from 12 low mass X-ray binaries (LMXBs). Although many of their detailed properties remain to be fully understood, it is now beyond doubt that these oscillations result from spin modulation of the thermonuclear burst flux from the neutron star surface. Among the new timing phenomena revealed by RXTE the burst oscillations are perhaps the best understood, in the sense that many of their properties can be explained in the framework of this relatively simple model. Because of this, detailed modelling of burst oscillations can be an extremely powerful probe of neutron star structure, and thus the equation of state (EOS) of supra-nuclear density matter. Both the compactness parameter $\beta = GM/c^2R$, and the surface velocity, $v_{\rm rot} = \Omega_{\rm spin}R$, are encoded in the energy-dependent amplitude and shape of the modulation pulses. The new discoveries have spurred much new theoretical work on thermonuclear burning and propagation on neutron stars, so that in the near future it is not unreasonable to think that detailed physical models of the time dependent flux from burning neutron stars will be available for comparison with the observed pulse profiles from a future, large collecting area X-ray timing observatory. In addition, recent high resolution burst spectroscopy with XMM/Newton suggests the presence of redshifted absorption lines from the neutron star surface during bursts. This leads to the possibility of using large area, high spectral resolution measurements of X-ray bursts as a precise probe of neutron star structure. In this work I will explore the precision with which constraints on neutron star structure, and hence the dense matter EOS, can be made with the implementation of such programs.

1. INTRODUCTION

Thirty five years after their discovery we are still largely in the dark as to the internal structure of neutron stars. The central densities of these objects are so high that an understanding of the equation of state (EOS) of the matter at their cores lies tantalizingly close yet still beyond the reach of the present predictive powers of theory. In an astrophysical context this is reflected in our inability to predict the radius, R, of a neutron star of a given mass, M. This quantity, the mass - radius relation, depends directly on the EOS. What we would sorely like to do is to plot the locations of real neutron stars in the mass - radius plane and in effect measure astrophysically the dense matter EOS.

There is a direct connection between the dense matter EOS and the fundamental physics of nucleon interactions. For example, Lattimer & Prakash [1] have demonstrated that accurate measurements of neutron star radii provide a determination of the pressure of matter at nuclear saturation density. This quantity is in turn directly related to the nuclear symmetry energy and the isospin dependence of the nuclear interaction. Moreover, constraints on the maximum mass of neutron stars would limit the presence of "exotic" condensates in neutron stars as well as bound the central density and thus the highest densities achievable in nature (see [1] and references therein).

2. MEASURING MASSES AND RADII

Precise inferences on the EOS require accurate measurements of neutron star masses and radii. For some young, binary neutron star pulsars, accurate masses have been deduced from relativistic orbital effects (see Thorsett & Chakrabarty [2]). However, little is known about the radii for this sample. For the older, accreting neutron star binaries, there is to date still precious little direct neutron star mass information. In a few cases where mass constraints can be attempted there is some evidence for "massive" neutron stars, with masses significantly greater than the canoncial $1.4M_{\odot}$ (see Orosz & Kuulkers [3], for example).

There are a number of different methods by which masses and radii can be estimated. Since the space here is inadequate to provide an exhaustive review of all these I will rather briefly discuss several areas of recent advancement and explore how the promise of these new findings can be realized with future, large area X-ray observatories.

2.1. Burst Oscillations

Burst oscillations were first discovered as strong, discrete peaks in Fourier power spectra of X-ray time series accumulated during thermonuclear X-ray bursts from some neutron star LMXBs (see Strohmayer et al. [4]). For an overview of their observational characteristics see Strohmayer & Bildsten [5] and the review by Muno elsewhere in this volume. In their discovery paper Strohmayer et al. [4] suggested that the burst oscillations result from spin modulation of the thermal burst flux, and their is now compelling evidence to support this conclusion. The initial evidence included; the large modulation amplitudes at the onset of bursts, the time evolution of the pulsed amplitude during the rise of bursts (Strohmayer, Zhang & Swank [6]), the coherence of the oscillations (Smith, Morgan & Bradt [7]; Strohmayer & Markwardt [8]; Muno et al. [9]), and the long term stability of the oscillation frequencies (Strohmayer et al. [10]). In the last few years the observations of highly coherent, orbitally modulated pulsations in a superburst from 4U 1636-53 (Strohmayer & Markwardt [11]), and burst oscillations at the known spin frequencies of two accreting millisecond pulsars; SAX J1808.4-3658 (Chakrabarty et al. [12]), and XTE J1814-338 (Strohmayer et al. [13]) have solidified the spin modulation paradigm.

In the context of using burst oscillations as probes of neutron stars, the importance of knowing that they are the result of photon emission from a non-uniform brightness pattern on the neutron star surface should not be underestimated. For many astrophysical phenomena a basic understanding of the emission geometry still remains controversial (an example is the X-ray emission from stellar mass black holes). The emission and propagation of photons from the surfaces of rapidly rotating neutron stars are strongly dependent on relativistic effects. For example, the amplitude of pulsations is affected by gravitational light deflection which depends on the compactness, β, and the shape (harmonic content) of the pulses is influenced by the rotational velocity, $v_{rot} = 2\pi \nu_{spin} \sin i$, which depends directly on the stellar radius, R, and the system inclination, i. A number of studies have attempted to use these effects to place constraints on the masses and radii of neutron stars. Miller & Lamb [14] explored the strength and harmonic content of pulses from point-like hot spots. They showed that knowledge of the angular and spectral dependence of the surface emissivity is important in obtaining accurate constraints. Nath, Strohmayer & Swank [15] modelled bolometric pulse profiles observed with the RXTE Proportional Counter Array (PCA) during the rising portion of X-ray bursts from 4U 1636-53. They concluded that models with a single hot spot did not yet strongly constrain the mass and radius. They modelled the emission from a circular, linearly growing hotspot, and included light deflection in a Schwarzschild spacetime. Weinberg, Miller & Lamb [16] have explored the pulse profiles produced by rotating neutron stars, including the rotational Doppler shifts and aberration of the emissivity. They concluded that pulse profile fitting is to be preferred over other indirect measures of the harmonic content, such as Fourier amplitudes. Muno, Ozel, & Charkrabarty [17] have explored the amplitude evolution and harmonic content of cooling phase burst oscillations from a number of different sources. They used the observed limits on harmonic content to constrain the location and size of the hot spot or spots responsible for the observed modulations.

An observational limitation of these attempts has been the inability to detect any harmonic signals in burst oscillations. However, burst oscillations from the accreting millisecond pulsar XTE J1814-338 have recently led to the first detection of significant harmonics (Strohmayer et al. [13]). The large number of bursts from J1814 and the good signal to noise achievable by co-adding bursts leads to the best chance to date to use burst oscillation signals detected by RXTE to constrain neutron star parameters. Such work is in progress at the time of this writing (Bhattacharyya et al. [18]).

2.1.1. *Pulse Profile Fitting*

As alluded to above, the detailed shapes of rotational modulation pulses are a unique function of a number of neutron star and binary orbital parameters. The modulation amplitude depends most sensitively on the size and shape of the surface emitting area, the viewing geometry, and the stellar compactness, β. The sharpness of the pulse profile (often conveniently expressed in terms of the strength of harmonics) is dependent on the relativistic beaming introduced by the surface rotational motion. The maximum observed surface velocity, v_{rot}, is given by $\Omega_{spin} R \sin i$. Since the spin frequency is known, the velocity is directly related to the stellar radius and the usually unknown inclination angle, i. Indeed, the pulse profile provides a unique signature of these different quantities. That is, if pulse profiles can be measured with infinite precision, then in principle, a unique solution for the parameters, M, R, and i can be obtained. Further, if pulse profiles can be measured with sufficient precision during the burst rise, *ie. as the X-ray emitting area grows*, then it should also be possible to see, in snapshot fashion, how the burning spreads and thus constrain the physics of nuclear flame propagation on neutron stars. In the next

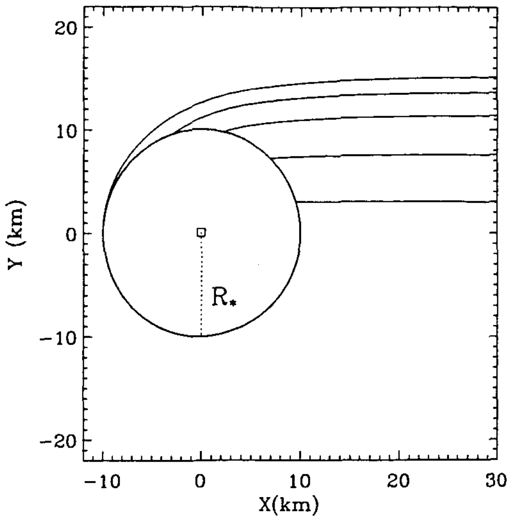

FIGURE 1. The trajectories of photons from the surface of a neutron star with a compactness $\beta = 0.284$. The observer is located at $x = +\infty$.

section I will explore the extent to which a future X-ray timing mission with $\approx 10\times$ the collecting area of PCA can place constraints on neutron star masses and radii by fitting the pulse profiles observed during the rise of X-ray bursts.

2.2. Spectroscopy: Lines and Continuum

It has been known for some time that continuum spectral analysis of Eddington limited X-ray bursts can in principle provide constraints on neutron star masses and radii (for a brief discussion see the recent reviews by Lewin, van Paradijs & Taam [19]; and Strohmayer & Bildsten [5]). The method has historically suffered from several systematic uncertainties; the unknown atmospheric composition, uncertainties in the intrinsic spectrum (leading to errors in deriving the effective temperature from the observed color temperature), as well as uncertainty in what fraction of the neutron star surface is emitting. With the discovery of burst oscillations, which provide a direct indication for asymmetries, this concern has taken on added importance. Although some of these problems remain, work in this area with the higher signal to noise RXTE data has continued (see for example Shaposhnikov, Titarchuk & Haberl [20]).

Perhaps the most direct method of measuring neutron star masses and radii is by the detection of spectral features (lines and edges) originating in their surface atmospheres. An observation of an identified spectral line gives the gravitational redshift, $1 + z = (1 - 2\beta)^{-1/2}$, at the neutron star surface, which provides a direct measurement of the compactness, β. Although reliable spectral features from neutron stars have been notoriously hard to find, recent observations of X-ray bursts from the LMXB 0748-676 with the XMM/Newton Reflection Grating Spectrometers have provided evidence for Fe XXVI absorption lines at a redshift of $z = 0.35$ (see Cottam, Paerels & Mendez [21]).

In addition to providing a direct measure of β, additional mass - radius information is encoded in the line profile. If the line width is dominated by rotation of the neutron star, then a measurement of it constrains the stellar radius through the surface velocity $v_{rot} = \Omega R \sin i$. For slowly rotating sources, many lines will be dominated by Stark (pressure) broadening (see Paerels [22]), which is proportional to M/R^2, so that in either the rotation or Stark broadening limits, accurate line identifications and profiles can provide enough information to determine both M and R uniquely.

For the burst oscillation sources, with known spin frequencies in the 200 - 600 Hz range, rotation should be the dominant broadening mechanism as long as the system inclination is not too small (see for example, Ozel & Psaltis [23]). The rotationally dominated line profiles also contain information on the fraction of the neutron star surface that is involved in the line formation. For example, emission from a fraction of the neutron star surface produces a characteristic "double-horned" line profile. Indeed, the relative strengths of the red and blue wings is sensitive to relativistic gravitational effects, such as frame dragging (Bhattacharyya [24]). The XMM observations suggest absorption lines with ≈ 10 eV equivalent width (Cottam, Paerels & Mendez [21]; Bildsten, Chang & Paerels [25]). In a later section I will explore briefly the sensitivity of future missions, such as NASA's Constellation-X, to such lines.

3. CONSTRAINTS FROM BURST OSCILLATIONS

An important capability provided by a larger collecting area is the increased sensitivity to harmonic content of the pulse profiles. As described above this provides information on the surface velocity and thus the stellar radius for neutron stars with known spin frequencies. Since both harmonic signals and the pulsed amplitude are strongest when the emitting area is small, I start by exploring the constraints that can be made by fitting the observed pulse profiles near the onset of bursts.

3.1. Physics of the Model

To do this I first generate a model of the time dependent pulse profile produced by a rotating neutron star. I build on the modelling described by Nath, Strohmayer & Swank [15]. The surface emission is assumed to be a blackbody with temperature, kT. The trajectories of photons emitted from the surface of a neutron star are in general curved. These effects are included by assuming that the external spacetime is the Schwarzschild metric. As an example, Figure 1 shows the paths of photons leaving the surface of a neutron star with compactness $\beta = 0.284$. Light bending allows a larger fraction of the neutron star to be seen by a distant observer, and thus the stronger the light deflection the smaller is the pulsed amplitude. Relativistic beaming and aberration of the specific intensity produced by rotation are also included, and arbitrary viewing geometries are also allowed. For the angular dependence of the specific intensity I use the limb-darkening law appropriate for a "grey" scattering atmosphere (see Chandrasekhar [26]). The profiles are calculated by summing the contributions from many small surface area elements on the neutron star surface. Finally, the spectrum in the rotating frame of the neutron star is appropriately redshifted to an observer at infinity. This amounts to a total of eight model parameters, the mass, M, the radius, R, the orbit inclination, i, the initial angular size of the hot spot, α_0, the angular growth rate of the spot, v_θ, the initial co-lattitude of the spot, θ_0, the surface temperature, kT, and the angular rotation rate of the neutron star, Ω. This geometry assumes that the rotation axis of the neutron star is perpendicular to the orbital plane. The level of sophistication in the model is similar to that employed by several other researchers, including; Weinberg, Miller & Lamb [16]; Muno, Ozel & Chakrabarty [17] and Braje, Romani & Rauch [27].

For the purposes of this work I have specialized to emission from an expanding, circular hot spot, however, more complex hot spot geometries can indeed be modelled. Although eight parameters are required to compute a pulse profile, some of these are known *a priori* or are highly constrained by the observations themselves. The observed continuum spectrum places good constraints on the surface temperature, kT, and for many anticipated targets the spin frequency is known. Moreover, the parameters which describe the size and growth rate of the hot spot are to a large extent constrained by the time dependence of the phase averaged lightcurve. In terms of the observed shape of the pulses, the most relevant parameters are the mass, radius, and initial location of the hot region. Indeed, the most important degeneracy amongst the parameters results from the fact that pulsed amplitude, which is a strong function of β, is also a strong function of hot spot location.

To obtain a model of the countrate profile seen in a real detector I take the physical photon spectrum seen at infinity and fold this through a realistic detector response function. For this I use a typical RXTE/PCA response matrix, but with the collecting area scaled up by a factor of 10. This produces a model of the predicted number of counts seen in the detector as a function of time (rotational phase). To determine the precision with which parameters can be estimated, a model profile computed using a set of fixed parameters is statistically realized a large number of times, and for each realization the best fitting set of model parameters is found using χ^2 minimization. As an example, Figure 2 shows a simulated pulse profile from the model. Figure 3 shows the resulting power density spectrum computed from this profile, and demonstrates that for this model, a harmonic signal is easily detected.

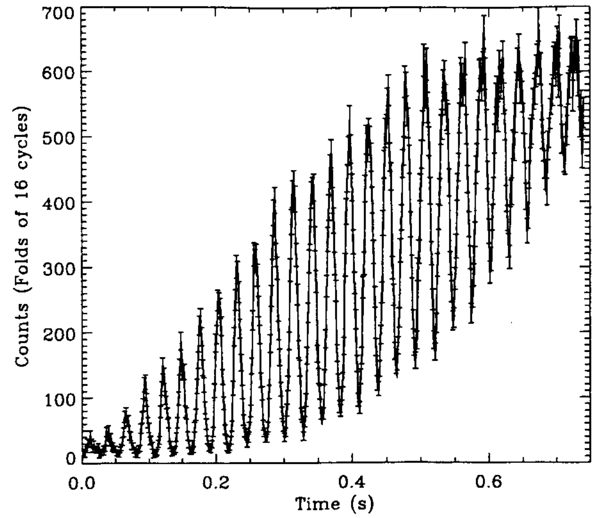

FIGURE 2. Simulated bolometric pulse profiles for the rising phase of an X-ray burst. For this simulation parameters were chosen to mimic bursts observed from the LMXB 4U 1636-53. I used $\beta = 0.284$, $R = 12$ km, a spin frequency of 582 Hz, and $kT_\infty = 2.7$ keV. Both the observer and the hot spot were located on the rotational equator. For clarity each pulse represents a folding of 16 successive cycles.

3.2. Results

Due to the large number of parameters and the computational burden required to compute models, it is time consuming to fully explore the entire range of the parameter space. As mentioned above, many of the parameters are known or well constrained by the continuum spectrum and phase averaged lightcurve. Therefore, to simplify the problem yet still retain useful estimates I began by computing models with the hot spot and viewing geometries fixed while allowing M and R to vary. The

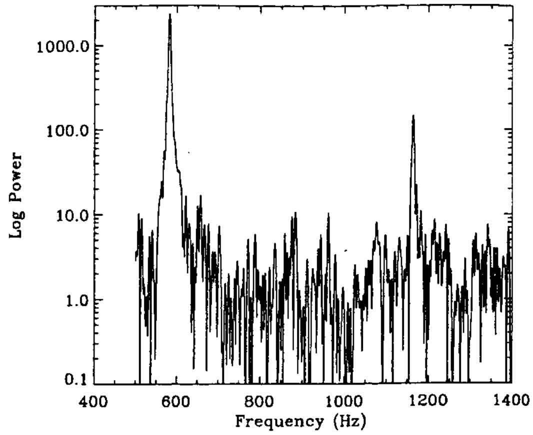

FIGURE 3. Power density spectrum computed from the lightcurve displayed in Figure 2. The vertical axis shows the Log of the Leahy normalized power. The fundamental (spin frequency) is at 582 Hz. The first harmonic near 1,164 Hz has a Leahy power near 200, and would be strongly detected.

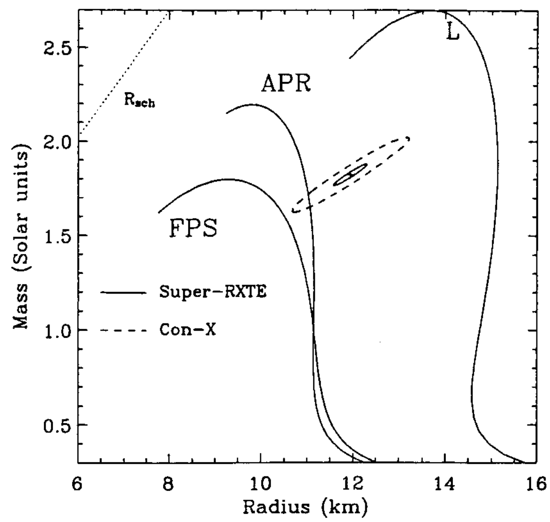

FIGURE 4. Mass and radius constraints achievable by pulse profile fitting with a factor of 10 increase in collecting area over RXTE/PCA. The solid and dashed ellipses show, respectively, the 1σ confidence contours for a "Super-RXTE" ($10\times$ PCA) detector, and for a Constellation-X sized collecting area. The results are for pulse fitting during the rise of a single X-ray burst using the model described in the text. The other curves show mass - radius relations for several neutron star EOSs; FPS (Lorenz, Ravenhall & Pethick [28]), L (Pandharipande & Smith [29]), and APR (Akmal, Pandharipande & Ravenhall [30]).

results from this analysis are summarized in Figure 4. I show an estimate of the confidence region in the mass - radius plane for pulse profile fits to a single burst from 4U 1636-53 (like that shown in Figure 2). The small solid contour represents the 1σ confidence region for a "Super-RXTE" instrument with $10\times$ the collecting area of the PCA. For this example the simulations were done for a neutron star with $\beta = 0.224$, and $R = 12$ km. I also show the 1σ contour for a collecting area appropriate to Constellation-X. As one can see from Figure 4 tight constraints on M and R are in principle achievable, in a statistical sense, with a factor of 10 increase in collecting area over RXTE/PCA. Also shown in Figure 4 are the mass - radius relations for several different neutron star EOSs. The level of statistical precision would be sufficient to strongly constrain the mass - radius relation.

3.3. Caveats: Systematic Uncertainties

The simulations indicate that on a statistical basis, tight constraints are achievable, however, one also has to think about possible systematic uncertainties in the modelling. After all, if the model is incorrect, then the parameter estimates are also likely to be incorrect. The two most important sources of systematic errors in the modelling are likely to be; uncertainties in the neutron star rest-frame spectrum (including, most importantly, the angular dependence of the emissivity), and the effects of photon scattering in the neutron star - accretion disk environment. In terms of the spectral modelling the most important quantity with regard to the pulse profiles is the angular dependence of the emissivity in the neutron star rest-frame. Miller & Lamb [14] showed that the angular dependence (in effect, intrinsic beaming of the spectrum) has an important effect on the amplitude and harmonic content, and thus on the pulse shape. If the angular dependence is not correct, then the mass - radius measurement will have some systematic deviation from the true values. It is not immediately obvious how to independently measure the angular dependence of the emissivity. However, it seems likely that with sufficient statistical precision the form of the beaming function can be uniquely constrained by the data, simply because an incorrect beaming function will not be able to adequately fit the data, but testing this idea will require more detailed simulations. It seems likely that we will have to also rely on more detailed theoretical modelling of the emergent spectrum during bursts. Fortunately, work in this area is still being done (see for example Majczyna et al. [31]; Shaposhnikov, Titarchuk & Haberl [20]).

We suspect that many X-ray binaries have electron scattering coronae in their immediate environs. Scattering of photons emitted by the neutron star in such a corona can smear out the pulsations, and thus alter the pulse shapes, this will also introduce a bias in the fitted parameters. One possible way to mitigate this uncertainty is by looking at many bursts. It is likely that the properties of the corona change somewhat with changes in source state and the overall non-burst spectrum. If for example the scattering optical depth changes from burst to burst, then this will cause a movement of the best fit parameters in the mass - radius plane. By including a scattering term in the modelling it may be possible to find the correct scattering description which brings the fits from many different bursts to a unique, consistent set of parameters. Again, this could be explored with more detailed simulations.

3.4. Theoretical Outlook

I have presented results based on a relatively simple description of the relevant physics. Although this should be sufficient for exploring the capabilities of future instrumentation, to fully exploit new observations will require significant theoretical resources. Fortunately, with the impetus provided by new observations there has been a corresponding growth in new theoretical thinking about some long standing issues concerning X-ray bursts.

- Ignition and spreading of nuclear flames on neutron stars. There has been great progress on this question in recent years. In a ground-breaking calculation Spitkovsky, Levin & Ushomirsky [32] have shown how rotation of the neutron star is crucial in understanding how and where flames ignite and how they spread around the star. This and future work opens up the possibility for detailed calculations of how the X-ray emitting region grows during a burst.
- Nuclear energy release and products of nuclear burning. A number of groups have been working on improving models of thermonuclear X-ray bursts, both by using more complete nuclear reaction networks and more realistic, multi-zone calculations (see for example, Woosley et al. [33]; Narayan & Heyl [34]; Schatz, Bildsten & Cumming [35]). These calculations provide new insight into the temperature, flux and composition evolution during bursts.
- Formation of spectra during thermonuclear X-ray bursts. Recent work has been done to further explore the angular dependence of the emergent spectrum as well as the formation of absorption lines in the atmosphere (see Majczyna et al. [31]; Bildsten, Chang & Paerels [25]).

These recent calculations represent some of the detailed input physics required to accurately model the time dependent X-ray flux from a bursting neutron star. Although a calculation putting all the different components together has not yet been performed, the required pieces of the puzzle are largely in place at the present time. It is not too hard to envision a future effort which attempts to incorporate these pieces into a unified model which could then be compared with observations from a future timing mission.

4. HIGH RESOLUTION SPECTROSCOPY

A path toward the neutron star EOS which should be less obscured with possible systematic uncertainties lies in high resolution X-ray spectroscopy. As described earlier, accurate line measurements and resolved profiles (with the correct line identifications) can provide enough information to obtain both M and R uniquely. Unfortunately it has been very difficult to detect any useful lines from neutron star atmospheres. Recent observations of the thermal emission from isolated or quiescent neutron stars with the high resolution capabilities of Chandra and XMM/Newton have been frustratingly devoid of spectral features (see for example Walter & Lattimer [36]; Burwitz et al. [37]; Drake et al. [38]; Pavlov et al. [39]).

A serious problem for non-accreting neutron stars is the high surface gravity which can sediment out the heavy, line forming metals on a surprisingly short timescale (see Bildsten, Chang & Paerels [25]). Because of this, accreting (and thus bursting) neutron stars may be more promising sources for line detections. An encouraging recent result is the detection of absorption features in bursts from the LMXB 0748-676 with XMM/Newton (Cottam, Paerels & Mendez [21]). They found ≈ 10 eV equivalent width features by co-adding 28 bursts seen with the RGS spectrometers. Their proposed identification with Fe XXVI $n = 2-3$ transitions gives a redshift of $z = 0.35$ from the neutron star surface. Although extremely exciting, this remains so far a single detection, and the ubiquity of such features in X-ray bursts in general remains to be established with further observations.

4.1. Future Capabilities

A number of future planned missions, such as the Japanese-led AstroE2, and NASA's Constellation-X, will have high resolution spectroscopic capabilities. Among these Constellation-X is the most ambitious in terms of X-ray collecting area, so one can ask the question, will these missions have the capability to study lines like those seen in the bursts from EXO 0748-696? To begin to address this question I have included in the model neutron star spectrum a gaussian absorption line with a 10 eV equivalent width at the rest energy of the transition identified by Cottam, Paerels & Mendez [21]. I then calculated the spectrum expected if the star is rotating and the whole surface is emitting. These spectra were then folded through a realistic Constellation-X re-

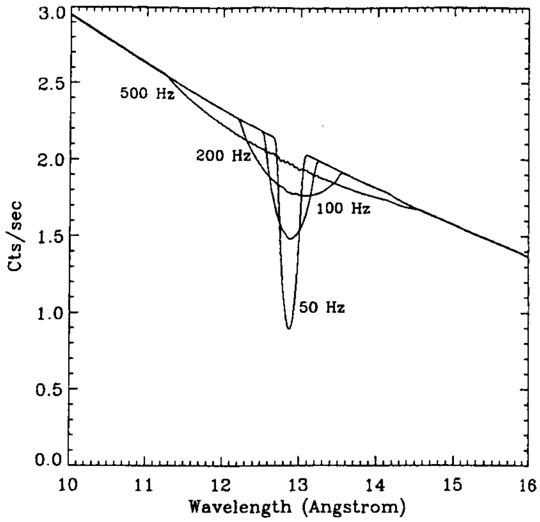

FIGURE 5. Absorption line profiles from the surface of a rotating neutron star. The profiles produced by contributions from the entire neutron star surface are shown for several different rotation rates. The observer is assumed to be looking in the rotational equator.

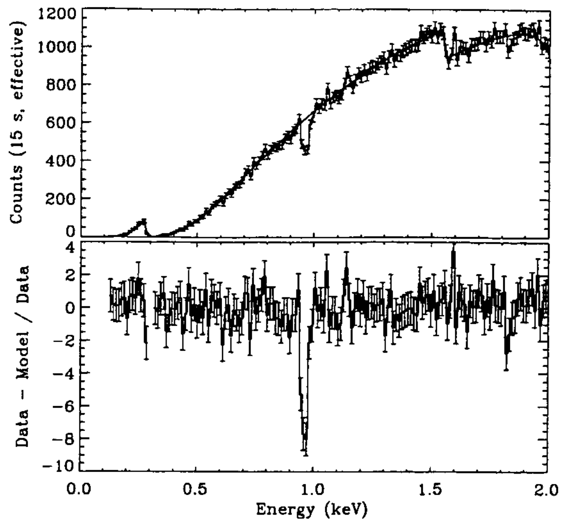

FIGURE 6. Predicted countrate spectrum (top) and residuals (bottom) in the Constellation-X calorimeter for 15 seconds of effective exposure at the peak flux of a bright burst from 4U 1636-53. The absorption line has an equivalent width of 10 eV, and the rotation rate of the neutron star was assumed to be 100 Hz.

sponse model to obtain predicted countrate spectra. As in the timing simulations I normalized the burst flux using typical bright bursts from the LMXB 4U 1636-53. The results are rather encouraging. First, Figure 5 shows several line profiles computed for a range of different rotation rates. For the fastest rotators, the widths approach $\Delta E/E \approx 0.1$. Figure 6 shows a simulation of the countrate spectrum for 15 seconds of effective exposure in the Constellation-X calorimeter at a flux equal to the maximum burst flux for 4U 1636-53. I use the flux from 4U 1636-53 as a characteristic value. Although this neutron star spins at 582 Hz, I have used rotation rates of 100 and 200 Hz in these simulations simply as representative values. Since many bursts last longer than 15 s, it is not unrealistic to expect that such a spectrum could be obtained from a single X-ray burst. The simulation indicates that in a statistical sense a line feature at this strength can in principle be detected. Figure 7 shows a second simulation, with a spin frequency of 200 Hz, and shows the response expected for the Constellation-X grating as well as the quantum calorimeter. These simulations, though still simplistic, suggest that high resolution detectors with large collecting areas will have important contributions to make for line studies of bursting neutron stars.

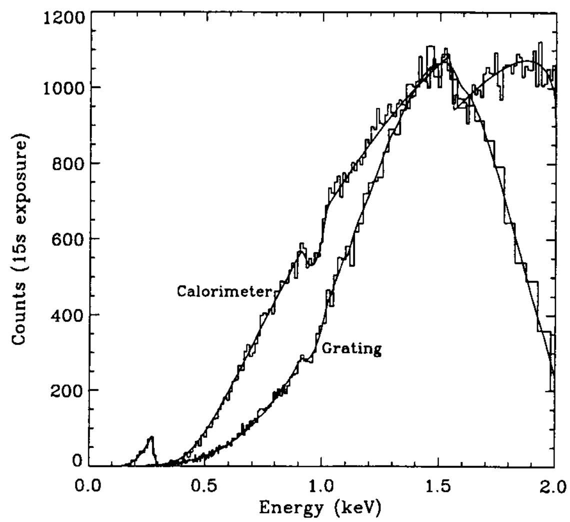

FIGURE 7. Predicted countrate spectrum in the Constellation-X calorimeter and grating for 15 seconds of effective exposure at the peak flux of a bright burst from 4U 1636-53. The absorption line has an equivalent width of 10 eV, and the rotation rate of the neutron star was assumed to be 200 Hz.

5. SUMMARY

RXTE observations have provided us with several new tools to probe the interiors of neutron stars. Perhaps the most promising is the detailed study of burst oscillation pulses, the shapes of which encode information about the neutron star mass and radius. I have shown that a future, large area timing mission with about 10× the collecting area of RXTE/PCA will provide data of sufficient statistical quality to allow stringent constraints on the neutron star mass - radius relation and thus the EOS of dense nuclear matter. With regard to interpretation of the data the primary concern will be the question of systematic uncertainties associated with the modeling. There has been substantial advancement in the theoretical tools needed for such modeling and the pace of these developments suggests that it is not unrealistic to expect that by the time a future mission flys, the impact of systematic uncertainties can be greatly reduced. Moreover, the new data themselves will likely provide new insights which cannot be anticipated at present. An additional strength of attacking the EOS problem using burst oscillations is that the signals are guaranteed to exist, and it is a virtual certainty that by studying these oscillations with a factor of 10 better sensitivity we will learn something new.

If atmospheric lines are indeed common in bursters, as the new XMM/Newton results may be indicating, then large area, high resolution spectroscopy could be the key to unlocking the secrets of the dense matter EOS. Current observations do not yet give us enough information to determine whether the lines are there in sufficient strength and number to really go after them. It is possible that more XMM observations will provide the answers. It also seems clear that Constellation-X will have important contributions to make with regard to spectral lines from bursters, and if lines are present in sufficient strength and number, then stringent EOS constraints may be possible.

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