DATA SELECTION CRITERIA FOR SPECTROSCOPIC MEASUREMENTS OF NEUTRON STAR RADII WITH X-RAY BURSTS
FERYAL ÖZEL1, DIMITRIOS PSALTIS1, TOLGA GÜVER2

ABSTRACT

Data selection and the determination of systematic uncertainties in the spectroscopic measurements of neutron star radii from thermonuclear X-ray bursts have been the subject of numerous recent studies. In one approach, the uncertainties and outliers were determined by a data-driven Bayesian mixture model, whereas in a second approach, data selection was performed by requiring that the observations follow theoretical expectations. We show here that, due to inherent limitations in the data, the theoretically expected trends are not discernible in the majority of X-ray bursts even if they are present. Therefore, the proposed theoretical selection criteria are not practical with the current data for distinguishing clean data sets from outliers. Furthermore, when the data limitations are not taken into account, the theoretically motivated approach selects a small subset of bursts with properties that are in fact inconsistent with the underlying assumptions of the method. We conclude that the data-driven selection methods do not suffer from the limitations of this theoretically motivated one.

Subject headings: dense matter — equation of state — stars:neutron — X-rays:stars — X-rays:binaries — X-rays:bursts

1. INTRODUCTION

Thermonuclear flashes on neutron stars have been used in the past decade to perform spectroscopic measurements of neutron star radii and masses (e.g., Majczyna et al. 2003; Özel 2006; Özel et al. 2009, 2010; Poutanen et al. 2014). The rich burst dataset (Galloway et al. 2008) from the Rossi X-ray Timing Explorer (RXTE) has not only allowed the measurement of the macroscopic properties of half a dozen of neutron stars but also initiated detailed studies of systematic uncertainties in these measurements. Even though the majority of sources showed bursting behavior that is highly reproducible (Güver et al. 2012a,b), a subset shows burst properties and evolution that are more complex.

A number of studies explored different approaches to identifying outliers in the burst samples of different sources that contaminate the statistical inferences in the measurements. In Güver et al. (2012a,b), we used a data-driven approach that employs a Gaussian mixture Bayesian inference to reject outliers. In particular, we looked at the cooling tails of X-ray bursts in the flux-temperature diagram, which would have yielded identical tracks among bursts of the same source in the absence of any astrophysical complexities. The degree of scatter we observed in the cooling tracks allowed us to measure the level of systematic uncertainty in the measurements, e.g., due to obscuration, reflection off the accretion disk, or uneven burning on the stellar surface, as well as to remove a small percentage of cooling tracks that clearly did not behave like the majority.

In an alternate approach, Poutanen et al. (2014; see also Kajava et al. [2014]) developed a theoretically motivated method to select bursts. They used the bursts

1 Department of Astronomy, University of Arizona, 933 N. Cherry Ave., Tucson, AZ 85721, USA
2 Istanbul University, Science Faculty, Department of Astronomy and Space Sciences, Beyazit, 34119, Istanbul, Turkey

Electronic address: E-mail: fozel@email.arizona.edu

Feryal Özel
	Dimitrios Psaltis
	Tolga Güver

Draft version September 11, 2015
the effective gravitational acceleration, i.e., how close the radiation flux is to the Eddington critical value. Because \( f_c \neq 1 \) in all relevant conditions, the normalization of the blackbody, defined as

\[
K \equiv (R_{BB}/D)^2 = \frac{F}{\sigma_B T_c^4},
\]

where \( F \) is the flux of the thermal emission and \( \sigma_B \) is the Stefan-Boltzmann constant, \((R_{app}/D)^2\), but rather to

\[
K = f_c^{-4}(R_{app}/D)^2.
\]

In Figure 1 we plot a typical evolution of the color correction factor for two of the models described in Suleimanov et al. (2012). It is evident in this figure that most of the evolution of the color correction factor occurs within 10% of the maximum flux (i.e., the Eddington flux corrected for temperature effects).

For a given neutron star, \((R_{app}/D)^2\) is fixed, and therefore, the blackbody normalization is expected to scale as \( f_c^4 \). Ideally, this expected evolution of the blackbody normalization can be used as a selection criterion for the method requires the selecting bursts that reach or exceed the Eddington limit, which is usually achieved by searching for evidence for photospheric radius expansion (PRE) episodes. Second, it requires accurately pinpointing the time of touchdown at the end of the PRE event and using only the data after this point to measure the evolution of the blackbody normalization. Finally, it requires obtaining a large number of counts at short integration times in order to resolve the evolution of the blackbody normalization with the rapidly decreasing flux.

We have discussed the criteria to select bona fide PRE bursts in Güver et al. (2012b) and will revisit this point in the next section. Because of the burst contrainations and instrumental limitations, burst spectra with RXTE are extracted using \( \sim 0.25 \, \text{s} \) integrations. Using a typical PRE burst from EXO 1745–248, we show in Figure 2 how this time binning affects both the time localization of the touchdown point and our ability to resolve the rapid flux evolution after it. In this example, within one 0.25 s
Looking for the evolution of the blackbody normalization as a function of flux fails not only on a burst-by-burst basis but also when it is applied to all the bursts from a given source. Fundamentally, the color correction factor for a given source depends on the local flux in the atmosphere, as measured by the effective temperature, and not on the total observed flux. The latter is affected by a number of factors, including the time bin averaging discussed above, as well as effects related to, e.g., partial obscuration of the neutron star surface or any reflection off of the accretion disk which are thought to be responsible for the outliers observed in some sources. This is of particular importance for the few sources that show a substantial number of outliers. The same effects also introduce a scatter to the blackbody normalization. Therefore, when the quantity $K^{-1/4}$ is plotted as a function of the measured flux, as shown in Figure 3 for the case of 4U 1608–52, the theoretically expected dependence is masked by the scatter. If we plot, instead, the quantity $K^{-1/4}$ against the observed color temperature, the scatter in the abscissa is reduced to a point where the theoretically expected correlation starts becoming evident.

In order to demonstrate the degree of scatter that even a small spread in the emitting radius can introduce to the expected correlations, we performed the following Monte Carlo simulation. We simulated mock observations of burst spectra using Model #17 of Suleimanov et al. (2012) for the dependence of the color correction factor on the effective temperature, which corresponds to a helium atmosphere with surface gravity $\log g = 14.3$. We assigned a spread in the radius of the emitting region with a Gaussian likelihood. We used these mock observations to infer the values of the blackbody normalization, color temperature, and flux that would have been measured under these conditions. Figure 5 shows the resulting relations between blackbody normalization, color temperature, and flux, for two cases: the left columns with a 5% spread and the right columns with a 15% spread in the emitting radius. Even for the small spread, the blackbody normalization appears a lot more tightly correlated with color temperature than with flux. For the larger spread, the latter correlation disappears and would have given the impression that the observations are inconsistent with theoretical expectations. Note that in performing these simulations, we have not included the significant smearing that occurs due to the size of the time bins that we discussed above or the statistical uncertainties that lead to correlated values between the blackbody normalization and the blackbody temperature (see, e.g., Figs. 3–8 of Ozel et al. 2013).

The above discussion demonstrates that the bursts selected in the data-driven approach of Güver et al. (2012a,b) show a spectral evolution that do not contradict theoretical expectations and can, therefore, lead to an unbiased sample for the measurement of neutron star radii (as reported by Ozel et al. 2013). Moreover, as we will show in the next section, devising selection criteria based on this theoretical expectation, without taking into account the inherent limitations of the data, leads to selecting precisely those bursts that do not reach the Eddington limit, therefore, violating the basic assumption of the procedure.
drawn, are shown by the red curves. In the left panels, we assigned a 5% Gaussian spread in the radius of the emitting region, whereas in the right panels, we assigned a 15% spread. Even for the small spread, the blackbody normalization appears a lot more tightly correlated with color temperature than with flux. For the larger spread, the latter correlation disappears and would have given the false impression the theoretical model of a bursting neutron star atmosphere. The theoretical model dependences, from which the mock observations were temporally (that is identified as the touchdown on the left is substantially during the radius expansion episode by more PRE burst and shows the increase in the blackbody normalization at half the Eddington flux levels. In contrast, the burst on the right is a bona fide photosphere never expanded, i.e., the blackbody normalization at what they marked as the touchdown point in their sample of Eddington limited bursts.

The identification of Eddington limited bursts relies exclusively on finding evidence for photospheric radius expansion, where there is a substantial increase in the inferred apparent radius of the photosphere above the value measured in the cooling tail, coincident with a decrease in the color temperature. Figure 4 shows the evolution of the spectral parameters in two bursts from 4U 1608–52. The burst on the left is representative of all the bursts selected by [Poutanen et al. 2014] as PRE bursts that follow the theoretical expectation. It is evident that even though the blackbody normalization and the color temperature oscillate in the beginning of the burst, the photosphere never expanded, i.e., the blackbody normalization never exceeded the asymptotic value at the cooling tail. In contrast, the burst on the right is a bona fide PRE burst and shows the increase in the blackbody normalization during the radius expansion episode by more than a factor of thirty. Furthermore, the flux at the point that is identified as the touchdown on the left is substantially (≥ 30%) smaller than the Eddington flux measured at touchdown for the burst on the right. Even though the method followed by [Poutanen et al. 2014] relies on measuring the evolution of the color correction factor at flux levels within 10% of the Eddington limit, the selection procedure failed to identify bursts that reach such flux levels.

It is also worth emphasizing that, even though [Poutanen et al. 2014] and [Kajava et al. 2014] characterize the selected bursts as long bursts occurring in the hard state, implying an underlying physical reason for this selection, their final sample represents neither the ones that occur in the hard state nor the longest observed bursts. This can be easily seen in Figure 7 that compares the distribution of (i) the burst locations in the color-color diagrams and (ii) the time from burst start to touchdown between the selected bursts and the entire sample for 4U 1608–52. Figures 3 and 4 of [Kajava et al. 2014] corroborate these observations and challenge the interpretation that the theoretically motivated burst selection has an underlying physical mechanism (e.g., one that is related to the different states of the accretion flow).

4. CONCLUSIONS

In this paper, we explored two approaches that have been proposed to select thermonuclear burst data for the spectroscopic measurements of neutron star radii. The first is the data-driven approach of [Güver et al. 2012a,b] that used a Bayesian Gaussian mixture algorithm to identify data outliers and measure the degree of systematic uncertainty in the measurements. The second is the theoretically motivated approach of [Poutanen et al. 2014].
Finally, we studied the sub-sample of bursts selected by Poutanen et al. (2014) for 4U 1608–52 using the theoretically motivated criteria without taking into account the data limitations discussed above. We showed that, contrary to the implicit assumption in the method, the bursts selected are not PRE bursts. Indeed, at no point during any of these bursts does the radius of the photosphere exceed the asymptotic radius measured during the cooling tails of the same bursts. Furthermore, the inferred touchdownfluxes of these bursts is 30% below the touchdown fluxes of the securely identified PRE bursts that reach the Eddington limit.

The quantitative analyses presented in this paper lead us to the conclusion that this theoretically motivated selection procedure is neither practical, given the limitations of the data, nor unbiased, given that it selects bursts that are inconsistent with its own assumptions. However, in the future, with the use of an X-ray detector with a larger collecting area and significantly fewer limitations when observing sources with high count rates, this could lead to useful radius measurements.

We thank all the participants of the “The Neutron Star Radius” conference in Montreal for helpful discussions and Gordon Baym, Sebastien Guillot, and Craig Heinke for comments on the manuscript. FÖ acknowledges support from NSF grant AST 1108753. TG acknowledges support from Istanbul University Project numbers 49429 and 48285.

REFERENCES
Galloway, D. K., Muno, M. P., Hartman, J. M., Psaltis, D., & Chakrabarty, D. 2008, ApJS, 179, 360
Güver, T., Özel, F., & Psaltis, D. 2012a, ApJ, 747, 77
Güver, T., Psaltis, D., & Özel, F. 2012b, ApJ, 747, 76
Kajava, J. J. E., Näätänen, J., Latvala, O.-M., et al. 2014, MNRAS, 445, 4218
Majczyna, A., & Madej, J. 2005, Acta Astronomica, 55, 349
Majczyna, A., Madej, J., Joss, P. C., & Różańska, A. 2005, A&A, 430, 643
Fig. 7.— The distributions (Left) of hardness in the persistent emission (as measured by the location $S_z$ along the color-color diagram) and (Right) of the time between burst start and touchdown, for (blue) all the bursts of 4U 1608−52 analyzed by Poutanen et al. (2014) and (red) for those selected by them as being consistent with the theoretical predictions. The selected bursts are neither the longer bursts nor the ones that occur in the hardest state, contrary to earlier claims.

Özel, F. 2006, Nature, 441, 1115
Özel, F., Baym, G., & Güver, T. 2010, Phys. Rev. D, 82, 101301
Özel, F., Güver, T., & Psaltis, D. 2009, ApJ, 693, 1775
Özel, F., Psaltis, D., Güver, T., et al. 2015, ArXiv e-prints, arXiv:1505.05155

Poutanen, J., Näätänen, J., Kajava, J. J. E., et al. 2014, MNRAS, 442, 3777
Suleimanov, V., Poutanen, J., & Werner, K. 2012, A&A, 545, A120