Revised
SLAC–PUB–9649
June 2003

X-ray Bursts in Neutron Star and Black Hole Binaries from USA and RXTE Data: Detections and Upper Limits[*]

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Abstract

Narayan and Heyl (2002) have developed a theoretical framework to convert suitable upper limits on type I X-ray bursts from accreting black hole candidates (BHCs) into evidence for an event horizon. However, no appropriate observational limit exists in the literature. In this paper we survey 2101.2 ks of data from the Unconventional Stellar Aspect (USA) X-ray timing experiment and 5142 ks of data from the Rossi X-ray Timing Explorer (RXTE) experiment to obtain a formal constraint of this type. 1122 ks of neutron star data yield a population averaged mean burst rate of 1.69×10^{-5} bursts s^{-1} while 6081 ks of BHC data yield a 95% confidence level upper limit of 4.9×10^{-7} bursts s^{-1}. This is the first published limit of this type for Black Hole Candidates.

Applying the theoretical framework of Narayan and Heyl (2002) we calculate regions of unstable luminosity where the neutron stars are expected to burst and the BHCs would be expected to burst if they had a surface. In this unstable luminosity region 464 ks of neutron

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[*] Work at SLAC was supported by Department of Energy contract DE-AC 03-76-SFO0515.

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star data yield an averaged mean burst rate of 4.1×10^{-5} bursts s^{-1} and 1512 ks of BHC data yield a 95% confidence level upper limit of 2.0×10^{-6} bursts s^{-1}, and a limit of $> 10\ \sigma$ that BHCs do not burst with a rate similar to the rate of neutron stars in these unstable regions. This gives further evidence that BHCs do not have surfaces unless there is some new physics occurring on their surface.

Submitted to the Astrophysical Journal

1. Introduction

In the nuclear burning model for X-ray bursts, a well-defined surface must exist for a type I X-ray burst to occur. Narayan & Heyl (2002) (hereafter NH02) performed a stability analysis of accumulating fuel on the surface of a generic compact object and showed that if Black Hole Candidates (BHCs) had surfaces, they would be expected to exhibit X-ray bursts. For this reason the lack of type I X-ray bursts in BHCs in stellar systems can be considered as evidence for an event horizon.

BHCs are typically distinguished from neutron stars using one of three methods. The primary method is direct dynamical measurements of their companions yielding masses for the compact objects that are $\gtrsim 3\mathrm{M}_{\odot}$, where a stable equation of state for a neutron star does not exist. The second method is that if timing and spectral analysis of the radiation from the accretion onto the compact object resembles other known BHCs the compact object is usually classified as a BHC. This typically means very little power above ∼500 Hz in a Fourier power density spectrum (Sunyaev & Revnivtsev 2000) and an energy spectrum that cannot be explained by a low temperature blackbody with an emission radius of ∼10 km (Rutledge et al. 2000). Thirdly, if an object exhibits type I burst behavior it is assumed to be a neutron star as this is strong evidence for the presence of a surface. This is the case for the compact object in GS 1826-238, which was first classified as a BHC based on timing and spectral behavior. It was only reclassified as a neutron star when type I X-ray bursts were detected (Ubertini et al. 1999).

Unstable thermonuclear burning on the surface of a weakly magnetized neutron star is the generally accepted model for type I X-ray bursts. Material accretes onto the surface until it reaches densities and temperatures sufficient for nuclear ignition. For some accretion rates, the burning is unstable and propagates around the star consuming all of the available fuel, resulting in an X-ray burst. This type of X-ray burst is characterized by a fast rise time of a few seconds and a decay time longer than a few seconds (up to several minutes). See Strohmayer & Bildsten (2003), Hansen & van Horn (1975), Lewin et al. (1995), Paczynski (1983), and Bildsten (2000) for a more detailed description. The type I X-ray bursts discussed in this paper are different from the X-ray superbursts recently discovered (e.g. Kuulkers et al. 2002). Type I X-ray bursts occur when helium on the surface of a neutron star ignites via the triple-alpha process forming carbon and oxygen. These bursts last ∼ a few seconds – 100s of seconds. Superbursts likely occur due to nuclear burning of carbon or by some other nuclear processes and last for several hours (see Cumming & Bildsten 2001 and Strohmayer & Brown 2002 for a review).

In this paper we present observations of neutron star LMXBs and BHCs from the USA Experiment as observational support for the work of NH02. We survey both neutron star and BHC systems for X-ray bursts and calculate burst rates for neutron stars and upper limits for the burst rate in BHCs, both overall and in the unstable burning regions calculated by NH02. This provides quantitative results which are important in any attempt to demonstrate formally the existence of event horizons using the method of NH02. In addition, it is important that any evidence in support or contradiction of the black hole model be aired to watch for evidence the standard picture may not be quite right (Peebles 2002; Babak & Grishchuk 2002).

2. Observations and Data Analysis

2.1. The USA experiment

USA is an X-ray timing experiment built jointly by the Naval Research Laboratory and the Stanford Linear Accelerator Center for the dual purpose of conducting studies of variability in X-ray sources and exploring applications of X-ray sensor technology (see Ray et al. 2001 for more details). USA was launched on 1999 February 23 aboard the Advanced Research and Global Observation Satellite (ARGOS), and took data until the mission ended in 2000 November. The primary observing targets were bright galactic X-ray binaries, with the goal of obtaining large exposures on a small number of sources.

The detector consists of two proportional counters sensitive in the range 1–15 keV with an effective area of about 1000 cm^2 each at 3 keV. One proportional counter failed very early in the mission and for the rest of the mission only one proportional counter was used. All the observations in this paper were made with one proportional counter only. Collimators define the field of view (FOV), which is approximately 1.2° FWHM circular. The Crab Nebula gives about 3500 cts s^{-1} at the center of the field of view in one counter. USA event timing is accurate to better than 32 μs. In the case of the LMXB Scorpius X$-$1 the count rates are so high that USA will auto-shutdown if it is directly pointed at the source. Thus, we must offset point at Scorpius X-1 so as to sample its source flux at about the 15% response point of the collimator.

2.2. RXTE Experiment

The RXTE experiment is an X-ray satellite composed of three instruments: the Proportional counter array (PCA), the high energy X-ray timing experiment (HEXTE), and the all sky monitor (ASM). The PCA is effective over the range 2-60 keV with 18% energy resolution at 6 keV. Data from the HEXTE instrument was not used in this paper. The ASM has three detectors sensitive in the 2-10 keV range and rotates to take a $\sim$ 90 second exposure on $\sim$ 75 sources several times daily. More detailed information on RXTE can be found in Jahoda et al. (1996).

2.3. Data Analysis

All binary sources with more than 30 ks of exposure time with the USA detector were scanned for bursts, including seven BHCs and seventeen neutron stars. The data analyzed were selected based on low background counting rate and a small $\leq 0.5^\circ$ pointing offset. The selection criteria result in less than 30 ks of analyzed data on some sources. The list of selected data analyzed in this paper is shown in Table 1. The columns are the source name, total time of good data analyzed, distance and mass of the source, classification of the source (BHC) Black Hole Candidate, Neutron Star (NS) and if a subdivision of Z or Atoll is clear. Additional information on the sources can be found in the references given. To supplement the USA BHC data, the RXTE public BHC data was analyzed for each USA BHC source analyzed in this paper, all public data for these sources as of April 2003, were analyzed.

2.3.1. Source Categorization Criteria

Because we are testing for the presence of bursts on objects purported to be black holes the classification criteria used must be crafted to avoid selection effects. Most importantly, the sources must not be classified based on the presence or absence of type I bursts. We have thus categorized our sources into neutron stars or black holes as follows.

Black Hole Candidates Each of the BHCs, with the exception of 4U 1630−472, have a known mass function or other mass estimate that give a lower mass limit of the compact object that exceed current theoretical limits for neutron stars. Since 4U 1630−472 does not have a mass limit requiring it to be a BHC, the data from this source is not used in calculating any of the bursting rates or bursting rate limits used later in this paper. Cygnus X-3 also has a debateable compact object. Cygnus X-3 has a mass function of $2.3 M_\odot$ (Schmutz et al. 1996) which does not rule out the possibility that the compact object is a neutron star. Therefore, the data of Cygnus X-3 is not used in calculating any burst rates or limits quoted in this paper. These two sources are included in Table 1 for completeness, to let the curious reader know that we did search the data of these sources and no X-ray bursts were detected.

Neutron Stars The following neutron stars were classified as such based on the presence of kilohertz Quasi-Periodic Oscillations (QPOs): Cygnus X-2, Aquila X-1, EXO 0748−676, GX 354−0 (4U 1728-34), 4U 0614+09, GX 349+2, Scorpius X-1, 4U 1735−445, X1636−536, GX 5-1, GX 340+0, and GX 17+2. The generally accepted view is that these kHz QPOs represent in some way an orbital frequency around the compact object. The frequency of an orbit around a compact object is:

$$\nu_{orb} = \left(\frac{GM}{4\pi^2 r_{orb}^3}\right)^{1/2} \approx 1200 \text{ Hz } \left(\frac{r_{orb}}{15 \text{ km}}\right)^{-3/2} M_{1.4}^{1/2} \quad (1)$$

where, $M_{1.4}$ is the mass of the compact object in units of $1.4\mathrm{M}_\odot$. From general relativity, no stable orbital motion is possible within the Innermost Stable Circular Orbit (ISCO). $R_{ISCO} = 6\mathrm{G}M/c^2 \approx 12.5 M_{1.4}$ km. At this orbit, the the frequency is $\nu_{ISCO} \approx (1580/M_{1.4})$ Hz (van der Klis 2000). From this, one can see that an object too massive to exist as a neutron star, $M \gtrsim 3\mathrm{M}_\odot$, can not demonstrate QPOs in the kHz range. For a list of known sources demonstrating kilohertz QPOs and a review of millisecond oscillations in X-ray binaries see van der Klis (2000).

The Rapid Burster is classified as a neutron star based on the presence of excess power in the kHz range during it's type II X-ray bursts as reported in Guerriero et al. (1997). The presence of significant noise above 500 Hz in an X-ray Power Density Spectrum (PDS) gives evidence for a neutron star according to Sunyaev & Revnivtsev (2000). In addition, spectral work from Chandra data gives evidence of a radius ~ 10 km for this source by looking at the type II X-ray bursts (Marshall et al. 2001), giving further evidence that this source should be classified as a neutron star.

The sources XB 1254-690 and Circinus X-1 do not have strong enough evidence to support that they are neutron stars independent of the past observed Type I X-ray bursts. Therefore, these sources will be included in Table 1 for completeness, but will not be included in any bursting rate or bursting rate limit calculations.

2.3.2. Detecting Bursts

The data were searched for bursts by visually inspecting the light curves, binned in 1 second intervals for USA data and 1/8 second intervals for RXTE data, of each observation several times. The visual scan looked for events that displayed properties consistent with type I X-ray bursts: large changes in flux with Fast Rise Exponential Decay (FRED) profiles, rise times of a few seconds, and decay times of several seconds or more. At the flux levels of all of the sources included in this work, this method will easily detect all type I X-ray bursts. Even if a burst in a BHC occurred with an order of magnitude less luminosity, as would be expected due to general relativistic effects see (Abramowicz et al. 2002), we expect to have detected them visually. Figure 1 shows an example of a typical type I X-ray burst found by USA in 4U $1735-445$. We did not search the USA data archive for superbursts. The longest continuous observation by USA was 20 minutes, with no less than 90 minutes between observations of the same source, making a burst spanning several hours difficult to detect. Unless specified, the term “X-ray burst” used in this paper refers to type I X-ray bursts.

2.4. Observations of Neutron Star Systems

Of the seventeen neutron stars that we studied (see Table 1), seven were observed to have type I X-ray bursts. These are: Aquila X-1, EXO 0748−676, GX 354−0, the Rapid Burster, 4U 1735−445 , GX 3+1, and MXB 1659−298. The Rapid Burster and GX 354−0 are separated in the sky by only 0.54°. Thus, they will be in the USA FOV at the same time making it possible to mistake a burst in one source for a burst in the other source, albeit attenuated by a factor of 0.53. For this reason, the data for these two sources were double counted in our analysis, meaning that an observation pointed at either source was considered to be a simultaneous observation of both sources. Therefore, the total observing time of these two sources will be twice the sum of the respective pointed observations. In theory, one may distinguish the Rapid Burster type I X-ray bursts from the GX 354−0 X-ray bursts. The GX 354−0 bursts nearly always show radius expansion and are much brighter than the Rapid Burster type I X-ray bursts (Kuulkers 2003; Fox 2003). In addition, the GX 354−0 bursts may display a harder spectrum than the Rapid Burster bursts (Fox et al. 2001; Fox 2003). However, we were not able to see definite evidence for radius expansion in the energy spectra of any of these bursts, and we were not able to distinguish two groups of bursts by any energy or timing analysis of the bursts from these sources, this may be due to the energy resolution of the USA experiment. The intensity difference can not be used to distinguish these sources since a collimator effect would disguise the burst intensity. Therefore, since the Rapid Burster and GX 354−0 are both known to display type I X-ray bursts regularly (Lewin et al. 1995; Fox et al. 2001), we can not distinguish the bursts from these two sources.

Several type I X-ray bursts were observed in the vicinity of the Rapid Burster in addition to the hundreds of type II bursts that occur continuously in this source when it is in a bursting state. We distinguished the type II bursts in this source from the type I bursts by their regular, “rapid-fire”, intervals. Spectral differences can be used to give a more definite distinction between the types of X-ray bursts. Type I X-ray bursts always have cooling blackbody spectra. Type II X-ray bursts do not show softening throughout the burst characteristic of a cooling blackbody. See Guerriero et al. (1999); Lewin et al. (1993) for more information on the Rapid Burster and type II X-ray bursts. Table 2 gives a list of bursts found in each source in our survey.

We did not detect bursts in ten of the seventeen neutron stars in our data: Cygnus X-2, Circinus X-1, 4U 0614+09, GX 349+2, XB 1254−690, Scorpius X-1, X1636−536, GX

5−1, GX 340+0, GX 17+2. Type I X-ray bursts have been detected in the past for each of these neutron star systems observed except for GX 349+2, Scorpius X-1, GX 5−1, and GX 340+0. Using the data from all seventeen neutron stars, we calculate an overall neutron star bursting rate $\lambda_{\rm NS} = 1.69 \times 10^{-5}$ bursts $\rm s^{-1}$. This results in an observed average time between bursts in our data, $R_{\rm NS} = 59.1$ ks, about 16.5 hours, from 1122 ks of data (double counting the GX 354−0 and Rapid Burster data).

2.5. Observations of Black Hole Candidates

Seven BHCs were searched for bursts: Cygnus X-1, XTE J1118+480, GRS 1915+105, XTE J1859+226, XTE J1550−564, 4U 1630−472, and Cygnus X-3. The total USA observing time for all of these BHCs is 1022 ks, the total observing time for RXTE is 5477 ks. No evidence of bursts was detected. Data from 4U 1630−472 and Cygnus X-3 were not used in any burst limit calculations. GRS 1915+105 showed several flares during the USA observations, close examination showed no distinct FRED profiles in these flares that would signal a type I X-ray burst. The USA observations were scheduled for repeated sampling to obtain many short observations over a long time period. The RXTE Target of Opportunity (TOO) observations repeatedly sampled transient sources during outbursts. As applied to transients this is particularly effective for the sources studied here: bursting may not occur in all ranges of mass accretion rate but the USA and RXTE observations sampled this critical parameter over the maximum extent possible. If BHCs burst in a narrow range of mass accretion rate, we are likely to have sampled that range. The USA experiment was fortunate that over its lifetime it was able to observe a number of very important transients, including systems with the largest known physical dimensions (GRS 1915+105) and the smallest (XTE J1118+480). USA and RXTE also devoted substantial time to Cygnus X-1 and GRS 1915+105, so that there was ample opportunity for any rare modes of bursting to be present in our observation of these sources.

Type I X-ray bursts are not a Poisson process. The time between bursts is a function of how long it takes to accumulate fuel to reach a critical density and temperature where unstable nuclear burning can occur. Burst intervals have been observed to be regular and irregular, and range from ~ 5 min to days or longer (Lewin et al. 1995), and are dependent on the accretion composition and rate (Strohmayer & Brown 2002). However, since our observation times were short compared to typical burst intervals and the revisit times were hours or longer, we are unlikely to observe consecutive bursts. Therefore, we treat these observations using Poisson statistics in order to place a numerical limit on the bursting rate. The probability of observing n events of a Poisson process is:

$$P(n) = (\lambda T)^n \, \frac{e^{-\lambda T}}{n!} \tag{2}$$

where: λ is the rate of bursts (bursts s^{-1}) and T is the total observing time. We will also define $R = 1/\lambda$ the average time between bursts. To set a limit on the burst rate to a confidence level of $CL = 95\%$ we calculate from eq. 2 for $n = 0$:

$$\lambda = -\frac{\ln(1 - CL)}{T} \tag{3}$$

where $P = 1 - CL$. For the values given, we calculate the upper limit of $\lambda_{\rm BHC} = 4.9 \times 10^{-7}$ bursts s^{-1} with a 95% confidence level. This is the first published survey to place quantitative limits on the rate of occurrence of bursts in a wide range of BHCs with a significant amount of data. As discussed in (Knight 2003) limits of these type emphasizing searches and null results are important to promulgate to the rest of the scientific community.

3. Discussion

In this section we discuss these observations in the context of the theoretical work of NH02. We start by converting our results to a format which allows easy comparison with theoretical predictions. Next, we show that our data in conjunction with the stability analysis of NH02, can place a probablity-limit on the existence of a surface on a BHC. Finally, we check our neutron star results for consistency with the NH02 analysis.

3.1. Luminosity Calculation

From the 17 neutron stars analyzed we calculate a bursting rate of $\lambda_{\rm NS} = 1.69 \times 10^{-5}$ bursts s^{-1}. This is comparable to rates found by other observers (see Strohmayer & Bildsten 2003). NH02 predict that the occurrence of Type I X-ray bursts is a strong function of $\log\left(\frac{L}{L_{\rm Edd}}\right)$, where $L_{\rm Edd}$ is the Eddington luminosity of the source, $L_{\rm Edd} = 1.3 \times 10^{38} M$ ergs s^{-1} (For H rich material) and M is the mass of the compact object in $M_\odot$. NH02 show that for certain values of $\log\left(\frac{L}{L_{\rm Edd}}\right)$ there can be stable burning and for other values there will be unstable burning leading to type I X-ray bursts. The exact ranges of L for stable accretion depend on the surface temperature of the compact object and its radius. For neutron stars, assuming a temperature at the base of the accretion layer of 10^8 K, the region of instability lies between $-1.5 \lesssim \log\left(\frac{L}{L_{\rm Edd}}\right) \lesssim -0.5$.

For each of the sources analyzed, we made a light curve in units of $\log\left(\frac{L}{L_{\rm Edd}}\right)$ for each observation. We then looked at the fraction of time sources were in the range of L where NH02 predict bursts should occur. In order to calculate the luminosity of the source, we fit a spectrum to a typical observation of the source using XSPEC (Dorman & Arnaud 2001). If distinct states in the source were evident from the source's hardness ratio, then observations from these states were fit separately. Most sources were fit using the Bulk Motion Comptonization (BMC) (Titarchuk et al. 1997) model in XSPEC with absorption and iron emission lines as needed. The BMC was the best fitting model to most of our data. After fitting a model to the data we obtained the model flux in the $0.2 - 30.0$ keV band. Since we know the USA count rate of the source for this flux, we are able to calculate a conversion factor from USA rate to source flux.

$$1 \text{ USA cts s}^{-1} \approx C \times 10^{-12} \text{ergs cm}^{-2} \text{ s}^{-1} \tag{4}$$

Where C is the measured conversion factor. C is between $7 - 12$ for most sources. This method yields a flux of 2.9×10^{-8}ergs cm^{-2} s^{-1} for the Crab Nebula in the $2 - 10$ keV band, which is within 5% of the accepted value of 2.8×10^{-8}ergs cm^{-2} s^{-1}. Based on this result, we believe the value of C to be correct in our observations at the 10% level. Utilizing this conversion and assuming isotropic radiation we find:

$$\log\left(\frac{L}{L_{\mathrm{Edd}}}\right) = \log\left(\frac{(\text{USA rate})(C \times 10^{-12})(4\pi d^2)}{1.3 \times 10^{38} M}\right) \tag{5}$$

where d is the distance to the source in cm and M is the mass of the compact object in $\mathrm{M}_{\odot}$. For the RXTE BHC data, a conversion factor was calculated to match the count rate per PCU in the PCA standard one data to the count rate seen by USA in the same source for an observation during the same day. The average count rate per observation was used to calculate this conversion. This conversion was calculated for each source to account for different detector response between the two experiments. After the RXTE data was converted to USA rate then the $\log\left(\frac{L}{L_{\mathrm{Edd}}}\right)$ was calculated following the method above.

Figures 2 and 3 give the resulting values of $\log\left(\frac{L}{L_{\mathrm{Edd}}}\right)$ for the BHC data and neutron star data analyzed in this paper. Figure 3 also shows the distribution of where we observed bursts in the data.

3.1.1. Luminosity Uncertainties

In order to estimate the uncertainty in the amount of data that falls within the bursting region we use eq. 5 to calculate an uncertainty in $\log\left(\frac{L}{L_{\mathrm{Edd}}}\right)$ for each source and use this uncertainty with Monte Carlo techniques . The distance and the mass contribute the largest systematic uncertainties to $\log\left(\frac{L}{L_{\mathrm{Edd}}}\right)$. The distances and masses used and the errors are given in Table 1. Uncertainties in L are estimated using error estimates on the mass $\sim 20\%$, if a definite uncertainty is not quoted in Table 1, and the distance $\sim 20\%$, if a definite uncertainty is not quoted in Table 1. We assume an uncertainty in C of 10%, based on estimates of the Crab luminosity, and assume the uncertainty in USA rate is negligible for all sources except GX 354−0 and the Rapid Burster. For these two sources the counting rate of one was contaminated with counts from the other as discussed in §2.4. We were able to deconvolve the two sources since we know the total USA counting rate while pointed at each source and we know the factor of contamination from the source off axis. For observations where one of these two sources was directly observed and the other was not directly observed within a few days, the RXTE ASM counting rate was used to estimate the rate of the off axis source. To do this, the ASM rate was converted to USA rate using 72 ASM counts s^{-1} as one Crab, and 3500 USA counts s^{-1} as one Crab. Therefore, for the Rapid Burster and GX 354−0, an error on the USA rate of 20% was used to calculate the errors on luminosity. This accounts for changes in counting rate of the off axis source between observations, and/or errors in the ASM counting rate. For each observation, a Gaussian deviate was calculated with the same mean as the measured value of $\log\left(\frac{L}{L_{\mathrm{Edd}}}\right)$ and a σ equal to the uncertainty value calculated for that source. Then the fraction of this simulated data in the bursting region was measured. We performed $10,000$ iterations in this manner and calculated the distribution of the fraction of data in the bursting region. We found that the distribution of the amount of data within the bursting region was rather tight, even though the individual errors on $\log\left(\frac{L}{L_{\mathrm{Edd}}}\right)$ were large. We found that, to a confidence level of 99.5%, 25% of our BHC data and 42% of our neutron star data fall within the region where one would expect bursts according to Narayan & Heyl (2002). Our analysis assumed that each of the sources analyzed were accreting Hydrogen rich material. If the accreted material has a large fraction of Helium, as do some bursters, then this will increase the value of L_{Edd}.

3.2. BHC Surface Limit

Narayan & Heyl (2002), calculated what would occur in a $10\mathrm{M}_{\odot}$ object if it were assumed to have a surface similar to that of a neutron star, and showed that the rate of bursts should be comparable to the rate in neutron stars. However, they find different regions of L where bursts should occur. For a $10\mathrm{M}_{\odot}$ object with a surface and a base temperature of 10^7 K, the regions where they expect to see bursts are approximately: $-2 \leq \log\left(\frac{L}{L_{\mathrm{Edd}}}\right) \lesssim -1.5$ and $-1 \lesssim \log\left(\frac{L}{L_{\mathrm{Edd}}}\right) \lesssim 0$. For the BHC data analyzed, at least 25% (1512 ks) of the data fall within this range to a confidence level of 99.5% using Monte Carlo estimates of uncertainty described above. Figure 2 shows the distribution of the observations analyzed in this paper in the units $\log\left(\frac{L}{L_{\mathrm{Edd}}}\right)$.

Considering only the neutron star data that fall in the luminosity range corresponding to unstable nuclear burning, we find that the 19 bursts occurred in 464 ks of data. This

464 ks value is the 99.5% confidence level on the amount of data within the bursting region based on the Monte Carlo techniques described above, thus accounting for uncertainties in the value of $\log\left(\frac{L}{L_{\rm Edd}}\right)$.

Using these data, we calculate the rate of bursting of neutron stars in the unstable region $\lambda_{\rm NS} = 4.1 \times 10^{-5}$ bursts s^{-1}, $R_{NS} = 24.4$ ks or $\sim$ 7 hours. Taking the Narayan & Heyl (2002) prediction for the rate of bursting in a BHC having a surface should be similar to that of a neutron star provided both are within regions of unstable L, we can calculate the probability of seeing no burst in our BHC data. From eq. 2, the probability of observing zero bursts in BHCs, if they exist with a rate similar to the rate observed in neutron stars, is $e^{-\lambda_{\rm NS}T} = 1 \times 10^{-27}$, where T, the amount of BHC data residing in the unstable region, is 1512 ks. Analyzing the data this way suggests that BHC do not have a surface as described by Narayan & Heyl (2002) to a confidence level of $> 10\ \sigma$. The limits and measured X-ray bursting rates can be found in Table 3. The columns are the bursting rate or limit calculated using all data analyzed, and then the bursting rate or limit calculated using only the data whose luminosity is within the bursting range calculated by NH02. This is the first such quantitative observational limit placed that quantifies what the lack of bursts means to the BHC theories.

One should point out that this is not definitive proof of the existence of black holes. Other authors have pointed out that there are other states of matter that may exist in these massive compact objects that do not show X-ray bursts but also do not possess event horizons. See Abramowicz et al. (2002) for several arguments along these lines. The authors in Abramowicz et al. (2002) outline arguments that the accreted material could immediately be converted to some exotic form that would not show X-ray bursts (Alford et al. 1998; Rapp et al. 1998). In addition, the argument is made that gravastars, if they exist, (Mottola & Mazur 2002) would be observational indistinguishable from black holes even though a gravastar exists without an event horizon or a singularity.

3.3. Neutron Star Observations Compared to Theory

In order to test the validity of the Narayan & Heyl (2002) predictions, we compare the occurrence of the type I X-ray bursts in neutron stars to the predicted occurrence calculated in Narayan & Heyl (2002). Specifically, after accounting for errors in measuring $\frac{L}{L_{\rm Edd}}$, we see no evidence that any of the observed neutron star bursts occurred when the source was not in the region of unstable burning where bursts would be expected. We investigated the neutron stars in which bursts were not observed, to determine if we expected to see bursts based on the theory put forth in Narayan & Heyl (2002). Of the neutron stars analyzed where we did not see bursts, we acquired 60 ks of data on GX 349+2 when it was in the region of luminosity where one would expect bursts. This is the largest amount of individual neutron star data in the bursting region in which we did not detect any bursts. Again, using Poisson statistics and assuming a bursting rate of $\lambda_{\rm NS} = 4.1 \times 10^{-5}$ bursts s^{-1} calculated above, we find that we have a $\sim 10\%$ chance of not seeing a burst in this source. Therefore, there is some reason to believe there is room to examine the boundaries of the bursting region predicting where the bursts will occur. However, it is worth noting that the USA data of X-ray binaries Scorpius X-1 and GX 349+2 are in the bursting region 43% and 74% of the time respectively (99.5% confidence level). In fact, one could use the fact that these are neutron stars that have never been observed to burst to place limits on the distances to these sources. Assuming a mass of $1.4 M_{\odot}$, GX 349+2 must not reside between $5.9^{+0.6}_{-0.5}$ – $9.7^{+1.0}_{-0.8}$ kpc and Scorpius X-1 must not reside between$2.5^{+0.6}_{-0.4}$ – $4.1^{+1.1}_{-0.6}$ kpc. The errors are based on 1 σ deviations in the observed rate from these sources. Previous distance estimates for GX 349+2 place it around the galactic center 5–8.5 kpc (Christian & Swank 1997; Cooke & Ponman 1991), and estimates place Scorpius X-1 at 2.8 ± 0.3 kpc (Geldzahler et al. 1999). Both of these estimates place these sources at the edge of our excluded region. The other two neutron star systems that we analyzed and have never been observed to burst, GX 340+0 and GX $5-1$ only spend $< 15\%$ and $< 2\%$ of their time in the bursting region. Therefore, it is likely that these sources are neutron stars that rarely, if ever, burst.

4. Conclusions

We present the burst catalog of the USA experiment X-ray binary data, and calculate limits on the rate of X-ray bursts in BHCs. We detected nineteen type I X-ray bursts in seven neutron stars. From our neutron star data we conclude that the average time between bursts in neutron stars is 59.1 ks, $\lambda_{NS} = 1.69 \times 10^{-5}$ bursts s^{-1}. The BHC data scanned showed no evidence for bursts. Therefore, we place a 95% confidence limit on the burst rate in BHCs to be $\leq 4.9 \times 10^{-7}$ bursts s^{-1} or $R \geq 470$ ks between bursts, based on USA and RXTE BHC data. The value of this upper limit is that it is at a level that is not easily pushed lower. This is because most BHCs are transients that, with some exceptions, last less than a few Megaseconds. The few BHCs that are relatively steady (primarily Cygnus X-1 but arguably GX 339$-$4 and GRS 1915$-$105) do not have more than a few tens of Megaseconds of observation. Thus, $10^{-6} - 10^{-7}$ bursts s^{-1} is a rough order of magnitude for the attainable limit. A sensitive all sky monitor might eventually reach a slightly lower value.

Applying the theoretical framework of Narayan & Heyl (2002), who claim that if BHCs have surfaces they will burst as prolifically as neutron stars if both are in a regime of unstable nuclear burning, we find that the BHCs in this regime do not burst with the same or higher rate as neutron stars to a confidence level of > 10 σ based on our limits. Therefore, these observations, analyzed according to the theory proposed by Narayan & Heyl (2002) leads us to believe that BHCs do not have a surface, as described in NH02, to a very high confidence level.

Work at SLAC was supported by Department of Energy contract DE-AC 03-76-SFO0515. Basic research in X-ray astronomy at the Naval Research Laboratory is supported by ONR/NRL. This work was also supported by the NASA Applied Information Systems Research Program. The authors would also like to thank Dr. Erik Kullkers, Dr. Lev Titarchuk, Dr. Jean-Pierre Lasota and the anonymous referee for useful comments.

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Table 1. USA observing times of X-ray binaries searched for bursts

Source	**Time (ks)**	**Dist. (kpc)**	**Mass estimate** ($M_\odot$)	**Class**[c]	**Reference(s)**
Cygnus X-1	449 - USA 1748 - RXTE	2	~ 10.1	BHC	Herrero et al. 1995
XTE J1118+480	183 - USA 119 - RXTE	1.9 ± 0.4	6.0 ± 0.36	BHC	Wagner et al. 2001 McClintock et al. 2001
GRS 1915+105	163 - USA 2358 - RXTE	12.5	14 ± 4	BHC	Greiner et al. 2001
XTE J1859+226	94 - USA 311 - RXTE	11	$\geq 7.4 \pm 1.1$	BHC	Filippenko & Chornock 2001 Zurita et al. 2002
XTE J1550−564	50 - USA 606 - RXTE	$3 - 6$	$9.7 - 11.6$	BHC	Orosz et al. 2002
4U 1630−472	46.2 - USA	10	??[a]	BHC	Augusteijn et al. 2001 Meyer-Hofmeister & Meyer 2001
Cygnus X-3	37.0 - USA 335 - RXTE	11.6	17^{+23}_{-10}[d]	BHC	Singh et al. 2002 Schmutz et al. 1996
Cygnus X-2	158.1	7.2 ± 0.11	1.4 ± 0.6	NS, b	Titarchuk & Shaposhnikov 2002 Orosz & Kuulkers 1999
Aquila X-1	93.2	$4 - 6.5$	~ 1.4[b]	NS A, b	Rutledge et al. 2001
EXO 0748−676	124.8	7.6	~ 1.4[b]	NS, b	van Paradijs & White 1995 Shahbaz & Kuulkers 1998
Rapid Burster	89.2	8.6	~ 1.4[b]	NS, b	Marshall et al. 2001
GX 354−0	81.1	$4.4 - 6.2$	~ 1.4[b]	NS A, b	Galloway et al. 2003
Circinus X-1	75.6	6.7 ± 1.2	$1.4 - 3.0$[e]	NS, b	Mignani et al. 2002

Table 1—Continued

					Saz Parkinson 2003
4U 0614+09	66.2	5	~ 1.4[b]	NS, b	Brandt et al. 1992 Christian & Swank 1997
GX 349+2 (Scorpius X-2)	81.6	5	~ 1.4[b]	NS Z	O'Neill et al. 2002 Christian & Swank 1997
XB 1254−690	51.7	12	??[f]	NS, b	Iaria et al. 2001 Christian & Swank 1997
Scorpius X-1	44.3	2.8 ± 0.3	1.4 ± 0.6	NS, Z	Titarchuk & Shaposhnikov 2002 Geldzahler et al. 1999
4U 1735−445	38.1	9.2	~ 1.4[b]	NS A, b	Seon et al. 1997 van Paradijs & White 1995
X1636−536	37.9	6.5 ± 0.2	~ 1.4[b]	NS, b	van Paradijs & White 1995 Christian & Swank 1997
GX 5−1	34.6	9	~ 1.4[b]	NS, Z	Christian & Swank 1997
GX 3+1	28.7	4-6	~ 1.4[b]	NS A, b	Kuulkers & van der Klis 2000 Christian & Swank 1997
GX 340+0	28.5	9.5-11.0	~ 1.4[b]	NS, Z	Christian & Swank 1997
GX 17+2	29.4	7.5	~ 1.4[b]	NS, Z, b	Christian & Swank 1997
MXB 1659−298	16.0	~ 10	~ 1.4[b]	NS A, b	Wijnands et al. 2002

[a] There is no dynamical mass estimate for 4U 1630−472. This source was not used in burst rate limit calculations.

[b] This neutron star mass is unknown, a value of $1.4M_\odot$ was assumed.

[c] Class of the source: BHC - Black Hole Candidate; NS - Neutron Star; A - Atoll source; Z - Z source; b - if bursts have been detected in the source in the past.

[d] The mass function for this source is $2.3M_\odot$, the nature of the compact object in this source is still unknown. This source was not used in burst rate limit calculations.

[e] Timing and spectral analysis of this source give evidence that Circinus X-1 is larger than $1.4M_\odot$ (Saz Parkinson 2003). This source was not used in burst rate calculations

[f] The nature of this source could not be identified independent of bursts, therefore this source was not used in burst rate calculations.

Table 2: Detected type I X-ray bursts of the USA experiment

Source	**Time of Burst Peak [MJD]**	**Rate Change [cts s^{-1}]**
Aquila X-1	51856.15684	1000 ⟶ 5000
EXO 0748−676	51614.54328	30 ⟶ 420
	51648.97544	40 ⟶ 420
	51648.41676	35 ⟶ 400
	51669.44317	40 ⟶ 470
	51687.50888	50 ⟶ 520
Rapid Burster / GX 354−0[a]	51482.51368	300 ⟶ 2700
	51487.23736	200 ⟶ 2100
	51492.94726	150 ⟶ 2100
	51861.23391	220 ⟶ 1100
	51861.93667	120 ⟶ 1500
	51491.82323	300 ⟶ 2000
	51743.31991	250 ⟶ 2600
	51812.96651	250 ⟶ 3000
	51816.00111	300 ⟶ 4000
	51817.41458	250 ⟶ 4400
4U 1735−445	51379.11730	400 ⟶ 3400
GX 3+1	51396.12709	200 ⟶ 1000
MXB 1659−298	51850.08140	180 ⟶ 400

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[a] The Rapid Burster and GX 354−0 are both in the USA FOV at the same time, therefore a burst in one source would be indistinguishable from a burst in the other.

Table 3. X-ray Burst Rates and Limits from the USA Experiment

	All Data [**bursts s^{-1}**]	**Data in Predicted Bursting Range** [**bursts s^{-1}**]
Neutron Stars	1.69×10^{-5}	4.1×10^{-5}
Black Hole Candidates[a]	$< 4.9 \times 10^{-7}$	$< 2.0 \times 10^{-6}$

[a] The 95% confidence level upper limit on the bursting rate in the BHCs.

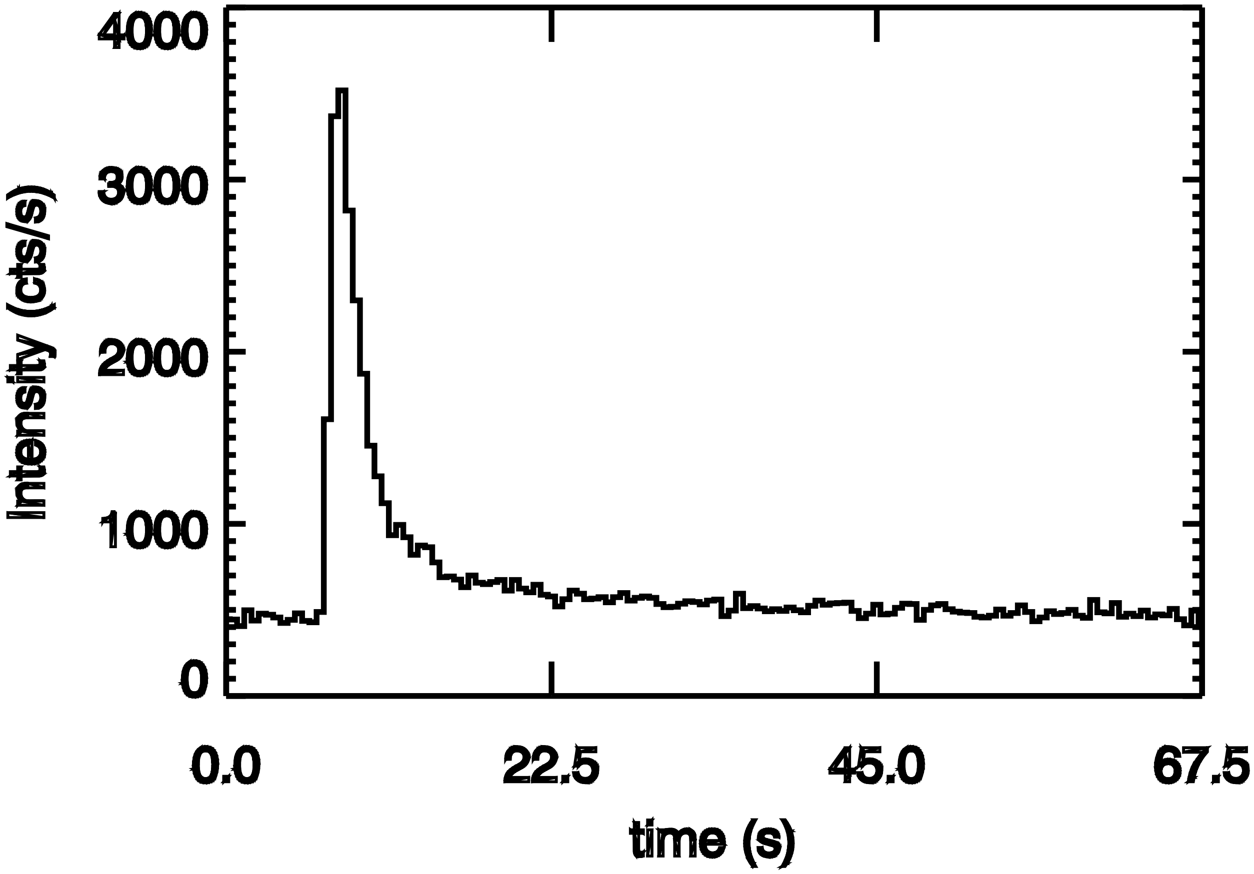

Fig. 1.— Example of a typical type I X-ray burst observed in 4U 1735 – 445 by USA.

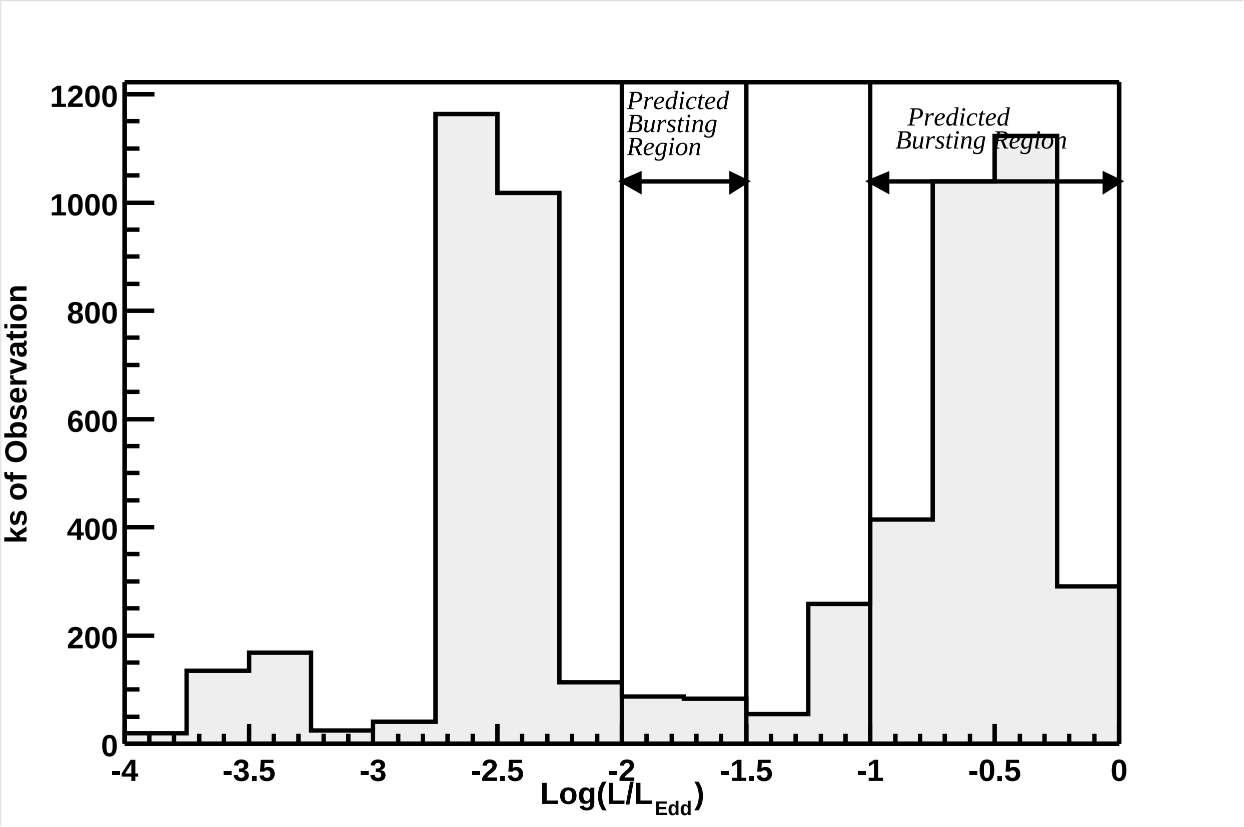

Fig. 2.— Distribution of the $\log\left(\frac{L}{L_{\rm Edd}}\right)$ for our BHC observations. The regions labeled "Predicted Bursting Region" are where Narayan & Heyl (2002) find unstable burning that should lead to type I X-ray bursts if a surface exists on a $10 M_\odot$ object.

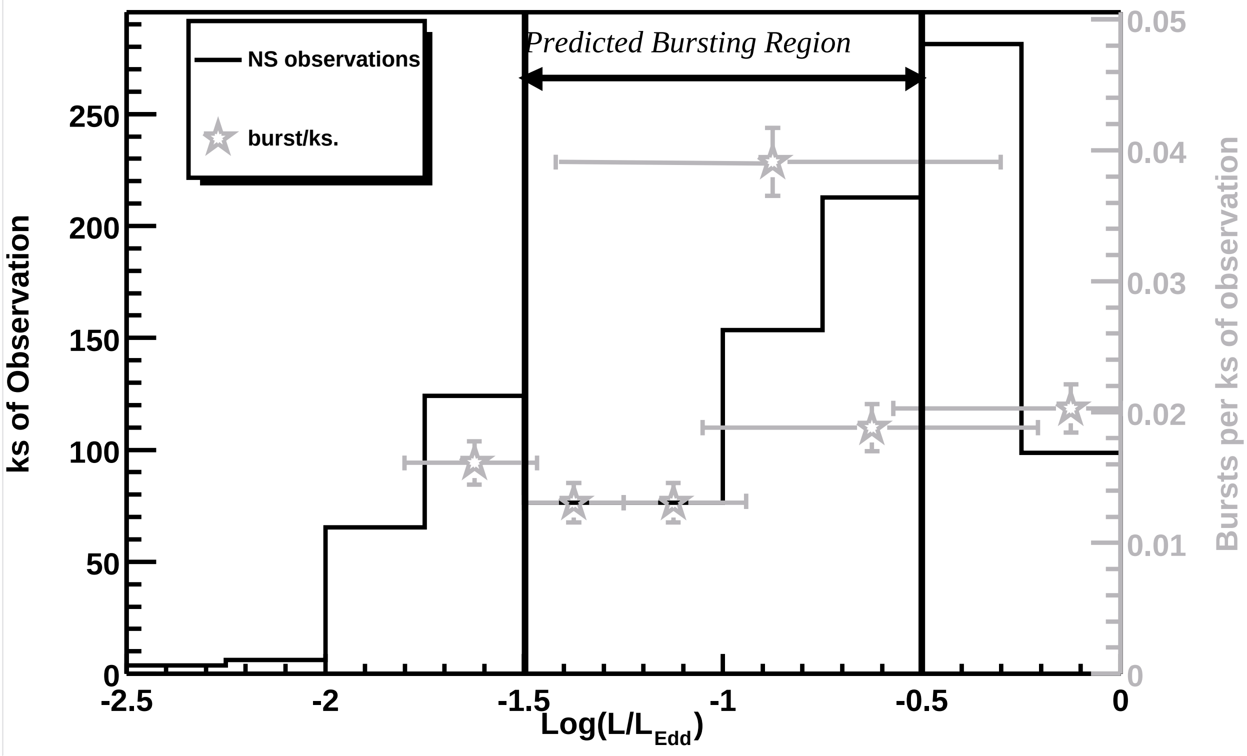

Fig. 3.— Distribution of the $\log\left(\frac{L}{L_{\rm Edd}}\right)$ for our neutron star observations. The solid histogram contains all the observations of the seventeen neutron stars that we analyzed in this paper. The region labeled “Predicted Bursting Region” is where Narayan & Heyl (2002) find unstable burning that should lead to type I X-ray bursts. The gray stars and the right ordinate show where the nineteen bursts detected by USA were observed, and show a bursting rate in that particular bin. The error bars reflect the uncertainties in the luminosity of the source(s) that had the burst(s) that went into the particular luminosity bin.