THE EFFECT OF THE MASS ACCRETION RATE ON THE BURST OSCILLATIONS IN 4U 1728 – 34

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ABSTRACT

We present a comprehensive study of the properties of nearly coherent brightness oscillations in a large sample of type I X-ray bursts observed from the low-mass X-ray binary 4U 1728 – 34. We have analyzed 547 ks of data of this source obtained with the Rossi X-Ray Timing Explorer over a 3 yr span from 1996 to 1999. The data contain 38 bursts, 16 of which show oscillations. We find no burst oscillations present when the inferred mass accretion rate of the system is lowest. Furthermore, we define a measure of the strength of the oscillations and find that this integrated strength increases with increasing mass accretion rate. This correlation is particularly evident within bursts detected only a few weeks apart and becomes less clear for bursts separated in time by several months to years. The correlation we find for 4U 1728 – 34 between the burst oscillations and the inferred accretion rate of the system is similar to that found for KS 1731 – 260 by Muno and coworkers, where the burst oscillations are only present at relatively high mass accretion rates. However, unlike the case for KS 1731 – 260, we find an anti-correlation in the bursts of 4U 1728 – 34 between the existence of episodes of photospheric radius expansion and the inferred mass accretion rate of the system. Moreover, we distinguish between burst oscillations present in the rise and in the decay phases of the burst and find that the bursts with oscillations only in the decay phase occur at intermediate accretion rates while those with oscillations in both the rise and the decay phases are concentrated at high inferred mass accretion rates. We discuss these results in the context of the theory of thermonuclear bursts and propose intrinsic differences in the neutron stars in KS 1731 – 260 and 4U 1728 – 34 as the origin of the different behaviors.

Subject headings: stars: individual (4U 1728 – 34) — stars: neutron — X-rays: bursts

1. INTRODUCTION

Low-mass X-ray binaries (LMXBs), systems in which a compact object accretes matter via Roche lobe overflow from a low-mass (<1 M\(_{\odot}\)) main-sequence companion, provide a fascinating window into the physics and dynamics of accretion disks and compact objects. When the compact object is a neutron star, the systems also permit detailed studies of the burning of the accreted material on the neutron star surface. Thermonuclear flashes (called type I X-ray bursts) occur in many LMXBs and are caused by explosive unstable burning of the accreted material. The properties of these type I X-ray bursts are affected by the rate at which the matter is deposited onto the neutron star (see, e.g., Lewin, van Paradijs, & Taam 1993 for an extended review of X-ray bursts). Thus, in order to understand these bursts, it is necessary to investigate the effect that variations in the mass accretion rate (M) onto the neutron star have on them. The first attempts at characterizing M in LMXBs centered around the persistent flux of the sources, since intuitively the larger the amount of matter accreted, the greater the amount of X-ray flux emitted. However, it has become clear that the persistent flux in general may not always be a good measure of M (e.g., van der Klis 1995) and hence cannot be directly correlated with the burst properties.

X-ray color-color diagrams were introduced to study subtle spectral changes in LMXBs (see, e.g., van der Klis 1995 and references therein). Hasinger & van der Klis (1989) studied the correlated rapid X-ray variability and spectral behavior of LMXBs and showed that they naturally fall into two distinct categories. These two groups are called the atoll and Z sources, after the tracks they trace out in the color-color diagram. The motion of the sources along these tracks is thought to be caused by changes in the mass accretion rate (Hasinger & van der Klis 1989), and it has become clear that the position of the sources on these tracks is a better indicator of the M of the system than the persistent flux (see van der Klis 1995 for LMXBs in general but Méndez 1999 for 4U 1728 – 34 in particular).

With the launch of the Rossi X-Ray Timing Explorer (RXTE) satellite, previously unknown high-frequency timing phenomena were discovered and now offer us new views of LMXBs (see, e.g., van der Klis 2000 for an extended review of the recently discovered timing phenomena in LMXBs). In particular, nearly coherent brightness oscillations with frequencies between 330 and 589 Hz were discovered in type I bursts from several sources (Strohmayer et al. 1996, 1997a; Smith, Morgan, & Bradt 1997; Zhang et al. 1997, 1998; Markwardt, Strohmayer, & Swank 1999; Wijnands, Strohmayer, & Franco 2000). These burst oscillations have extremely high coherence values (\(\nu/\Delta\nu > 4000\); Strohmayer & Markwardt 1999; Muno et al. 2000), high amplitudes (up to ~50% rms in the 2–60 keV bandpass; Strohmayer, Zhang, & Swank 1997b; Strohmayer et al. 1998b), and they exhibit long-term frequency stability of up to years (Strohmayer et al. 1999a; Muno et al. 2000). These properties strongly argue for the rotation of the neutron star as the origin of the burst oscillations. In this interpretation, during a thermonuclear burst inhomogeneities in the fuel or in the fuel burning may arise, causing “hot spots” on the surface of the neutron star. These hot spots rotate with the spin frequency of the star and periodically modulate the X-ray flux.

These oscillations can be present in the rise of the bursts, very near the burst onset, and/or in the decay phase (or tail) of the bursts. When the oscillations are observed in the tail, their frequency can increase by 1–3 Hz, reaching an asymp-
totic limit as the bursts progress (see, e.g., Strohmayer et al.
1998b). It has been proposed that this frequency increase is
calwed by thermal expansion of the thermonuclear burning
layer on the stellar surface. Heating from the burning
expands the shell by several tens of meters at the onset of
the burst. Due to angular momentum conservation, this
layer will slow down, causing the observed frequency to
decrease. During the decay of the burst, the burning layer
settles back on the neutron star surface and spins up,
causing the frequencies to increase again. In this picture, the
asymptotic limit represents the true neutron star spin fre-
quency (Strohmayer et al. 1997b). The atoll source 4U
1636–53 has shown evidence for a subharmonic to the
oscillation frequency, indicating the possible existence of
two nearly antipodal hot spots (perhaps at the magnetic
poles; Miller 1999). This detection of the subharmonic fre-
quency raises issues about how the burning front propa-
gates on the surface of the neutron star and how the fuel can
be concentrated in two antipodal regions.

The burst oscillations in the atoll source KS 1731–260
have been recently studied by Muno et al. (2000). They
reported the discovery of a correlation between the inferred
$M$ of the system and the presence of oscillations in the
bursts. They find that the bursts from KS 1731–260 can be
separated into two classes: the so-called “fast” bursts,
which occur at relatively high $M$, exhibit oscillations, and
show episodes of photospheric radius expansion (the expan-
sion of the neutron star photosphere occurring when the
energy released during the burst is higher than the Edding-
ton limit), and the “slow” bursts, which occur at lower $M$,
do not exhibit oscillations, and do not show photospheric
radius expansion episodes. Studies like these require a large
sample of bursts observed over a considerable range of acc-
retion rates. Such databases have so far been obtained only
for the persistent sources because the outbursts of the X-ray
transients are rare and when they do occur only a limited
number of X-ray bursts are seen. In this paper, we will
concentrate on the persistent source 4U 1728–34.

The LMXB 4U 1728–34 is a prolific source of type I
X-ray bursts (Basinska et al. 1984) and one of the best
studied LMXBs. It has been classified as an atoll source
(Hasinger & van der Klis 1989; Méndez & van der Klis
1999), and it exhibits most of the behaviors seen in those
systems. It was the first neutron star LMXB to show twin
kilohertz quasi-periodic oscillations (kHz QPOs) in the per-
sistent emission and the first to show burst oscillations
(Strohmayer et al. 1996, 1998a; with an asymptotic value of
363.9 Hz). The kHz QPOs in 4U 1728–34 have been
studied by several groups (Strohmayer et al. 1996; Ford &
van der Klis 1998; Méndez & van der Klis 1999; Di Salvo
et al. 2001). The burst oscillations in 4U 1728–34 have
been investigated by Strohmayer et al. (1996, 1997b, 1998a)
and Strohmayer & Markwardt (1999). In this paper we present a
study of the behavior of oscillations in a set of 38 type I
X-ray bursts from 4U 1728–34, observed over a wide range of
mass accretion rates. We found that 4U 1728–34 is
similar to KS 1731–260 in that the oscillations are only
present in bursts that occur at high $M$ (Muno et al. 2000).
However, contrary to the case of KS 1731–260, we find an
anticorrelation between the presence of photospheric radius
expansion episodes in the bursts and the inferred mass ac-
cretion rate of the system. We also find a more complicated
behavior with $M$ for the oscillations in the rise and in the
decay phases of the bursts.

This paper is organized as follows: In § 2 we describe in
detail the observations being used for this study. In § 3 we
explain the methods used to characterize the persistent
emission and the burst properties and the techniques used
to study the burst oscillations. In § 4 we discuss the spectral
states (i.e., the color-color diagram) of the source. In § 5 we
discuss the behavior of the burst oscillations and study
them in correlation with other burst characteristics and the
spectral state of the source. Finally, in § 6 we discuss the
implications of these correlations for our current under-
standing of 4U 1728–34 in particular and for thermonu-
clear burning on the surface of neutron stars in general.

2. THE OBSERVATIONS

The source 4U 1728–34 was observed with the Pro-
portional Counter Array (PCA) on board RXTE on many
occasions between 1996 February 15 and March 1 (here-
after referred to as observation set AO1), 1997 September
19 and October 1 (AO2), and 1998 September 30 and 1999
January 18 (AO3). The actual observation dates are listed in
Tables 1, 2, and 3 along with the main properties of all 63
observations in our sample. In total, our database consists
of 547.4 ks of on-source data. The AO1 observations were
obtained with epoch 1 gain settings for the PCA instrument,
while the AO2 and AO3 observations correspond to epoch
3 gain settings. Hereafter, when we refer to an observation
we mean those data that can be identified by a unique
observation identification number (ObsID; see Tables 1, 2,
and 3). All five PCA detectors were on during all obser-
vations except for 3.6 ks during the observation with ObsID
20083-01-01-020 and 3.6 ks during 20083-01-03-020. No
bursts were detected during those two intervals, so we have
excluded those data from our study.

In total, we observed 38 bursts, which we label numeri-
cally in Tables 1, 2, and 3. The analysis of portions of our
data have already been published in the literature. Stroh-
mayer et al. (1996) reported the discovery of burst oscil-
lations using burst 5 in our sample, and Strohmayer et al.
(1997b) presented a temporal and spectral analysis of bursts
3, 4, and 5 and reported the existence of oscillations in
bursts 4 and 5. Méndez & van der Klis (1999) published a
color-color diagram of AO1 and a portion of AO2 data (see
also Di Salvo et al. 2001).

A variety of data modes were available for each obser-
vation set in addition to the Standard 1 and Standard 2
modes. Because the same data modes were not always avail-
able across observation sets, we describe here the extant
modes and how they were used to extract the quantities of
interest to this study. The AO1 data were obtained in one
burst trigger mode (TLA1s_10_249_1s_5000_F), two burst
catcher modes (CB125us1M00_249_H with 122 $\mu$s time
resolution in one energy channel; CB8ms64M00_249_H
with 8 ms resolution in 64 channels) and one single-bit
mode (SB125us0_249_1s with 122 $\mu$s resolution in one
channel), in addition to the Standard 1 (with 0.125 s time
resolution in one energy channel) and Standard 2 (with 16 s
time resolution in 64 energy channels) data modes. The
burst catcher modes provide data typically for 1 s before
the burst onset and for as long as the count rate remains
above the trigger level. In our case the trigger level was set to
5000 counts s$^{-1}$, and the length of data ranges from 13 to 16 s
for these modes. For AO2 we had the same burst trigger and
catcher modes available as during AO1. However, instead
of the single-bit mode we now had one event mode
TABLE 1
AO1 OBSERVATIONS OF 4U 1728 – 34 (RXTE PCA EPOCH 1)

| ObsID (10073-01) | Date (1996) | Start Time | End Time | $T_{\text{exp}}$ (ks) | $F_{\text{avg}}$ | Burst |
|------------------|-------------|------------|----------|-----------------------|-----------------|-------|
| 01-0000          | Feb 15      | 11:51      | 18:49    | 11.8                  | 4.1             | 1     |
| 01-01            | Feb 15      | 18:49      | 00:02    | 13.1                  | 4.2             | 2     |
| 02-0000          | Feb 16      | 00:02      | 06:22    | 13.1                  | 4.4             | 3     |
| 02-00            | Feb 16      | 06:22      | 10:14    | 10.1                  | 4.7             | 4, 5  |
| 03-0000          | Feb 16      | 15:48      | 22:11    | 12.3                  | 4.7             | 6     |
| 03-00            | Feb 16      | 22:11      | 01:19    | 7.7                   | 4.8             |       |
| 04-0000          | Feb 18      | 11:08      | 18:49    | 13.4                  | 3.4             | 7     |
| 04-00            | Feb 18      | 18:49      | 23:49    | 10.5                  | 3.2             | 8     |
| 06-0000          | Feb 22      | 11:32      | 18:53    | 8.9                   | 2.0             |       |
| 06-00            | Feb 22      | 18:53      | 00:02    | 10.1                  | 3.3             | 9     |
| 07-0000          | Feb 23      | 21:16      | 05:16    | 18.2                  | 2.3             |       |
| 07-00            | Feb 24      | 05:16      | 06:45    | 3.2                   | 2.3             | 10    |
| 08-0000          | Feb 24      | 17:51      | 01:26    | 15.5                  | 2.4             | 11    |
| 08-00            | Feb 25      | 01:26      | 05:11    | 8.5                   | 2.4             |       |
| 09-0000          | Feb 25      | 20:45      | 04:45    | 17.9                  | 2.5             | 12    |
| 09-01            | Feb 29      | 23:09      | 00:02    | 1.1                   | 2.8             |       |
| 10-01            | Mar 1       | 00:02      | 05:45    | 13.3                  | 2.8             |       |

*a Total on-source time per ObsID.

*b Average flux in units of $10^{-9}$ ergs s$^{-1}$ cm$^{-2}$ with uncertainties of 1%-3% (90% confidence interval).

Finally, the time series of the burst spectra were obtained from the event mode for AO2, the combined data modes for AO3, and the 8 ms resolution burst catcher mode for AO1 (hence there is at most 16 s of time-resolved spectra for each burst in AO1).

3. THE ANALYSIS

To characterize the persistent emission, we calculated average fluxes for each observation. The fluxes were obtained by fitting (using Xspec; Arnaud 1996) a cutoff power-law spectrum to the background-subtracted Standard 2 data. A Gaussian line around 6 keV was added to the spectral model and allowed to vary in order to obtain acceptable fits. Since we are only interested in the flux of the persistent emission, we did not investigate the significance of this feature further (but see, e.g., Di Salvo et al. 2000). The

TABLE 2
AO2 OBSERVATIONS OF 4U 1728 – 34 (RXTE PCA EPOCH 3)

| ObsID (20083-01) | Date (1997) | Start Time | End Time | $T_{\text{exp}}$ (ks) | $F_{\text{avg}}$ | Burst |
|------------------|-------------|------------|----------|-----------------------|-----------------|-------|
| 01-0000          | Sep 19      | 05:52      | 10:40    | 11.3                  | 4.8             | 4     |
| 01-01            | Sep 19      | 12:29      | 15:02    | 6.6                   | 4.8             | 13    |
| 01-0200          | Sep 20      | 07:32      | 14:03    | 14.7                  | 4.1             | 14    |
| 01-02            | Sep 20      | 14:03      | 16:29    | 6.2                   | 4.8             |       |
| 02-0100          | Sep 21      | 15:43      | 21:05    | 13.8                  | 5.0             | 15, 16|
| 02-00            | Sep 22      | 05:59      | 13:59    | 3.3                   | 4.4             | 17    |
| 03-01            | Sep 23      | 23:50      | 00:41    | 1.3                   | 4.8             |       |
| 03-0000          | Sep 24      | 09:14      | 17:14    | 18.9                  | 5.7             |       |
| 03-00            | Sep 24      | 17:14      | 18:18    | 3.7                   | 5.4             |       |
| 04-0000          | Sep 26      | 12:29      | 19:55    | 17.9                  | 3.9             | 18, 19|
| 04-01            | Sep 27      | 09:18      | 16:43    | 18.1                  | 3.2             | 20, 21|
| 03-0200          | Sep 30      | 04:33      | 10:39    | 13.2                  | 3.9             |       |
| 03-02            | Sep 30      | 10:39      | 14:05    | 7.1                   | 3.9             |       |
| 04-0200          | Oct 1       | 06:09      | 14:09    | 17.5                  | 3.6             |       |
| 04-02            | Oct 1       | 14:09      | 15:18    | 3.5                   | 3.7             |       |

*a Total on-source time per ObsID.

*b Average flux in units of $10^{-9}$ ergs s$^{-1}$ cm$^{-2}$ with uncertainties of 1%-3% (90% confidence interval).
resulting averaged fluxes in the 3–18 keV range are listed in Tables 1, 2, and 3. In order to verify the reliability of our fluxes, we fitted other spectral models (three-component models: a Comptonized spectrum plus either a multicolor disk blackbody or a plain blackbody plus a Gaussian line around 6 keV; see, e.g., Di Salvo et al. 2000). We find that these alternative models give the same average flux of the persistent emission within the quoted errors.

To generate the color-color diagram, for AO1 we define the soft color as the logarithm of the ratio of the count rate in the energy range 2.9–4.5 keV to the count rate in the range 4.5–6.3 keV. Similarly, we define the hard color as the logarithm of the ratio of the count rate in the range 6.3–9.0 keV to that in the range 9.0–18.2 keV. For AO2 and AO3 the energy ranges are slightly different: 3.0–4.4 keV to 4.4–6.2 keV for the soft color and 6.2–9.1 keV to 9.1–18.2 keV for the hard color. The colors were calculated from background-subtracted light curves from the Standard 2 data and hence have 16 s time resolution. However, to reduce the errors on the colors we averaged them in 256 s intervals.

We searched for bursts by generating light curves of the Standard 1 data with 0.125 s resolution. We found 38 bursts in our data set. We have numbered the bursts according to time and have listed their main properties in Table 4. The start time of the burst is determined from the first time bin in the background-subtracted light curve with a count rate above 1000 counts s⁻¹. We characterize the bursts by obtaining time-resolved series of spectra. We extracted dead time–corrected spectra of 0.125 s duration for a time interval of 20 s during the bursts.

We perform a standard spectrum analysis of these bursts using Xspec. As a background spectrum we used the spectrum of an interval of 10 s of the persistent emission before the burst onset. While the true background spectrum during a burst may differ from that of the persistent emission before the burst (van Paradijs & Lewin 1986), this procedure will suffice to establish the existence of photospheric radius expansion episodes. Using this procedure we find that the spectra of X-ray bursts are well fitted by a simple blackbody model (Swank et al. 1977).

From the spectral fits we extracted time series of temperature, radius of the emitting region, and measured flux. The peak measured fluxes are listed in Table 4. From the best-fit parameters and the blackbody assumption, we can calculate a peak bolometric flux using $F_{bol} = 4\pi R^2 \sigma T^4$, where we assume a distance to the source of 5.1 kpc (Di

| ObsID (30042-03) | Date (1998-1999) | Start Time | End Time | $T_{exp}$ (ks) | $F_{avg}$ (ergs cm⁻² s⁻¹) | Burst |
|------------------|------------------|------------|----------|---------------|----------------------------|-------|
| 01-00 ............ | Sep 30           | 07:11      | 11:52    | 10.4          | 4.4                        | 22    |
| 02-00 ............ | Oct 7            | 05:05      | 09:49    | 11.1          | 5.9                        |       |
| 01-01 ............ | Oct 23           | 22:35      | 23:08    | 1.9           | 3.8                        |       |
| 02-01 ............ | Oct 24           | 00:15      | 01:09    | 2.5           | 3.8                        |       |
| 03-01 ............ | Oct 24           | 01:47      | 03:46    | 4.8           | 3.8                        | 23    |
| 01-02 ............ | Oct 26           | 20:57      | 21:34    | 1.7           | 3.9                        |       |
| 01-03 ............ | Oct 26           | 22:33      | 23:10    | 2.1           | 3.9                        |       |
| 04-00 ............ | Oct 27           | 00:09      | 03:19    | 6.9           | 3.9                        |       |
| 01-04 ............ | Oct 29           | 01:44      | 02:43    | 3.5           | 4.0                        |       |
| 05-00 ............ | Oct 29           | 03:20      | 06:37    | 7.0           | 3.9                        |       |
| 06-00 ............ | Nov 1            | 02:30      | 07:26    | 9.8           | 4.0                        | 24, 25|
| 07-01 ............ | Nov 2            | 22:29      | 23:30    | 3.6           | 4.0                        | 26    |
| 07-00 ............ | Nov 3            | 00:05      | 03:18    | 7.4           | 4.0                        | 27    |
| 08-00 ............ | Nov 5            | 04:00      | 07:29    | 6.7           | 4.1                        |       |
| 09-00 ............ | Nov 10           | 13:17      | 14:15    | 2.2           | 4.4                        |       |
| 09-02 ............ | Nov 10           | 16:31      | 17:07    | 2.1           | 4.4                        |       |
| 10-00 ............ | Nov 10           | 18:26      | 20:19    | 4.9           | 4.4                        | 28    |
| 10-01 ............ | Nov 10           | 21:07      | 21:54    | 2.8           | 4.4                        |       |
| 11-00 ............ | Nov 10           | 22:26      | 03:16    | 10.8          | 4.3                        | 29    |
| 12-00 ............ | Nov 11           | 14:50      | 14:52    | 17.9          | 4.3                        | 30, 31|
| 13-00 ............ | Nov 11           | 22:26      | 03:13    | 10.4          | 4.4                        | 32    |
| 14-02 ............ | Nov 16           | 06:34      | 07:00    | 1.5           | 5.2                        |       |
| 14-01 ............ | Nov 16           | 08:14      | 09:08    | 3.2           | 5.2                        |       |
| 14-00 ............ | Nov 16           | 09:52      | 10:47    | 3.2           | 5.1                        | 33    |
| 15-00 ............ | Nov 16           | 13:09      | 19:15    | 14.9          | 5.1                        | 34    |
| 16-00 ............ | Nov 17           | 00:12      | 07:36    | 17.1          | 4.5                        | 35    |
| 17-00 ............ | Nov 17           | 13:02      | 14:00    | 3.4           | 4.0                        | 36    |
| 18-00 ............ | Jan 16           | 07:51      | 11:52    | 9.9           | 3.1                        |       |
| 19-01 ............ | Jan 17           | 04:50      | 05:34    | 2.6           | 3.1                        |       |
| 19-00 ............ | Jan 17           | 06:11      | 10:10    | 10.0          | 3.2                        | 37    |
| 20-00 ............ | Jan 18           | 22:39      | 01:18    | 5.4           | 3.3                        | 38    |

* Total on-source time per ObsID.

b Average flux in units of $10^{-9}$ ergs cm⁻² s⁻¹ with uncertainties of 1%–3% (90% confidence interval).
To determine which bursts exhibit episodes of photospheric radius expansion, we inspect by eye their temperature and radius time series. We then verify this assessment by calculating hardness ratios as a function of time during the burst. In Figure 1 we show a typical burst with a photospheric radius expansion episode. The drop in the hardness ratio in Fig. 1 indicates the beginning of the radius expansion phase. This behavior is confirmed by a simultaneous decrease in the blackbody temperature (Fig. 1c) and increase in the inferred radius of the emitting region (Fig. 1d), while the bolometric flux remains constant (Fig. 1e).

To search for oscillations in the bursts, we employ the $Z^2$ statistic described by Strohmayer & Markwardt (1999; see also Buccheri et al. 1983). The main reasons for this choice are that it does not require binning and its probability density is $\chi^2$ distributed even for small numbers of events (X-ray photons in our case). Since the oscillations are highly sinusoidal, we consider only the $Z^2_{12}$ (see Strohmayer & Markwardt 1999). We generate data segments of 2 s in duration with centroids separated by 0.25 s (hence they are not independent) and search for power in the vicinity of the previously found oscillation frequency of 363 Hz (Strohmayer et al. 1996). We set the detection threshold at $Z^2_{12} = 14$. This is equivalent to a single-trial significance of a little better than $1 \times 10^{-3}$. Since pulsations are known to exist in this source, we do not need to search a wide frequency space, and we therefore have few effective trials.
show oscillations are shown in Figure 2. We established a measure of the strength of the oscillations by integrating the rms amplitude of the oscillations over their duration in the burst, ignoring the wings of the power features that fall below our detection threshold. We refer to this measure of strength as the integrated strength.

4. THE COLOR-COLOR DIAGRAM OF 4U 1728–34

The color-color diagram of 4U 1728–34 in Figure 3a shows a track typical of atoll sources (Hasinger & van der Klis 1989; see also Méndez 1999). It is important to note that the shift in the color-color diagram of the track for AO1 with respect to the tracks of AO2 and AO3 is not an intrinsic behavior of the source but is due to the difference in gain settings. Our observations of 4U 1728–34 sampled the entire atoll track, though not during a single observation set. Both AO1 and AO3 exhibit the complete island-state track, from the extreme island state at the upper right of the color-color diagram, believed to be the state with the lowest mass accretion rate, to just before the island state–banana branch vertex (hereafter referred to simply as “the vertex”). Only during our AO2 observations was 4U 1728–34 found in the banana branch. This observation set covers the entire banana branch, from the lower banana branch on the left corner to the upper banana branch on the bottom rightmost portion of the track, where the mass accretion rate is thought to be the highest. Our color-color diagram looks very similar in shape to those published previously for 4U 1728–34 (Méndez & van der Klis 1999; Piraino, Santangelo, & Kaaret 2000; Di Salvo et al. 2001). Our island state appears somewhat longer, but this difference is due to the different choice of colors and disappears when similar colors are used.

To determine the position of the source in the color-color diagram prior to each burst, we determine the color of the source from an interval of 320 s before the burst, ending 16 s prior to the onset of the burst. The results can be seen in Figure 3a, where the numbers indicate the spectral state of the source just prior to the occurrence of each burst. From the figure it is clear that we detected bursts throughout almost the entire track, from the extreme island state to the upper banana branch although not in the uppermost part of the upper banana branch. However, it is not yet clear whether this is due to a real lack of bursts at the highest $M$
or due to the limited amount of data so far obtained when 4U 1728 − 34 was at such high accretion rates.

To verify the spectral state of the source prior to each burst, average power density spectra (PDS) were obtained by integrating over the entire length of the continuous data train prior to each burst (ranging in duration between 300 and 3600 s). Figure 4a shows the PDS of the source prior to burst 22, which is typical of the source when it is in the extreme island state. This PDS clearly shows band-limited noise at frequencies above 100 Hz, with no high-frequency QPOs, a bump around 10 Hz, a flat spectrum at low frequencies, and a break around 1 Hz, typical for the island state (see, e.g., van der Klis 1995). At the vertex, e.g., prior to burst 21, the source PDS (Fig. 4b) shows a kHz QPO and a break around 20 Hz typical of the lower banana branch in transition to the island state. Figure 4c shows the PDS for the source prior to burst 15, when 4U 1728 − 34 is in the upper banana branch. The PDS shows a typical featureless power-law noise component. As mentioned above, the difference in gain settings between epochs 1 and 3 causes a
shift in the island-state tracks between AO1 and AO3. To see where the AO1 track might join the AO2 track if there were no gain differences, we show in Figure 4d the PDS of the source prior to burst 3. This PDS is very similar to that of burst 21 (Fig. 4b), indicating a transition between the island state and the lower banana branch.

5. THE BEHAVIOR OF BURST OSCILLATIONS

5.1. The Burst Oscillations and the Inferred Mass Accretion Rate

As shown in Figure 5, we find no correlation between the average flux of the persistent emission prior to the bursts and the existence or integrated strength of the burst oscillations. However, if the presence and possibly the strength of the burst oscillations is correlated with the mass accretion rate, as was the case in KS 1731−260 (Muno et al. 2000), then the lack of correlation is not surprising because, as already mentioned in § 1, the flux is not a robust tracer of the mass accretion rate. Instead, a better measure of $M$ is the position of the source on the atoll track in the color-color diagram.

In Figure 3b, we plot all bursts in the color-color diagram, the bursts that do not show oscillations with diamonds and those that do with circles. For bursts with oscillations, the size of the circles is proportional to the integrated strength of their oscillations as defined in § 3. From this figure it is clear that bursts with oscillations occur only on the bottom part of the diagram where the accretion rate is thought to be highest, i.e., near the vertex and on the banana branch. Close inspection of this figure reveals that the integrated strength of the burst oscillations generally increases with decreasing hard color; i.e., the oscillations become stronger and/or longer in duration as the inferred mass accretion rate of the system increases. This relation is especially evident for bursts within a single observation set and hence separated in time by only a few days to a few weeks, but it is not so clear for bursts from different

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**Figure 4.**—Representative power density spectra from bursts occurring when 4U 1728−34 was in the extreme island state (a), vertex between island state and banana branch (b, d), and upper banana branch (c).

**Figure 5.**—Average persistent emission fluxes obtained from a power-law fit to the data prior to each burst. The dashed lines separate the bursts during AO2 observations from those of AO1 and AO3. Bursts without burst oscillations are shown with asterisks, while bursts with burst oscillations are shown with circles whose size is proportional to the integrated strength of the oscillations (see text). Burst 3, which is unusually dim and has a slow rise compared to the rest of the bursts in AO1, is marked with a square. The flux uncertainties are 1%−3% (90% confidence intervals).
observation sets, separated in time by up to years (i.e., between the AO1 and AO2 data sets).

5.2. The Burst Oscillations and the Burst Flux

In Figure 6 we show the peak burst fluxes for the bursts in our sample. Bursts without oscillations are marked with asterisks, while bursts with oscillations are shown with circles whose radius is proportional to the integrated strength of the oscillations. Burst 3, which is unusually dim and has a slower rise compared to the rest of the bursts in AO1, is marked with a square. The first trend evident from Figure 6 is that the bursts in our AO2 observations (except for bursts 20 and 21) have considerably lower peak fluxes than those in our AO1 and AO3 observations. We also observe that the bursts without oscillations have on average higher peak fluxes. Furthermore, among the bursts with oscillations in a single observation set (AO1 or AO2), the dimmest bursts also have the strongest oscillations. This correlation does not hold when we consider bursts from AO1 and AO2 together.

5.3. The Burst Oscillations and Bursts with Photospheric Radius Expansion

In their study of KS 1731 – 260, Muno et al. (2000) found that all the bursts with episodes of photospheric radius expansion occur at high mass accretion rates and they all show oscillations. They go further to distinguish between oscillations occurring during the rise of the burst and those occurring during the cooling tail of the burst. They note that oscillations in the rise of bursts are not correlated with episodes of photospheric radius expansion since burst 7 in their sample exhibits such oscillations but not a photospheric radius expansion episode. However, their data suggest that all bursts with oscillations in the decay portion of the burst do exhibit photospheric radius expansion episodes.

A careful look at Figure 3c reveals a different picture for 4U 1728 – 34. Bursts with photospheric radius expansion episodes (squares) occur throughout the entire island state and at the vertex but not in the banana branch itself. This is precisely the opposite of the behavior in KS 1731 – 260, where all bursts with episodes of photospheric radius expansion lie in the banana branch, at the highest M. We also note that all seven bursts from our sample that lie in the banana branch (but not bursts 20 and 21, which lie near the vertex) have very low peak measured fluxes (see Fig. 6), while all the bursts with photospheric radius expansion in the KS 1731 – 260 study are “fast” bursts that show high peak fluxes.

The behavior of the bursts in 4U 1728 – 34 is richer still. Muno et al. (2000) hinted at a possible difference between the oscillations observed during the rise of bursts and those observed in the cooling tails of the bursts. If we make this distinction, we find in our sample two bursts with oscillations only in the rise, seven bursts with oscillations in both the rise and the tail, and seven bursts with oscillations only in the tail. Representative bursts of each of these categories are shown in Figure 2. In Figure 3d we can see that these differences in the burst oscillations are also borne out on the color-color diagram. Bursts with oscillations only in the decay tail of the burst (squares) are seen at intermediate M, in the island state and the vertex. Those bursts with oscillations in both the rise and the tail of the bursts (triangles) are found only at high M, in the banana branch. The two bursts with oscillations only in the rise of the burst are shown with circles, and they appear in the upper banana branch, at the highest inferred M. However, with only two such bursts it is difficult to determine whether or not their location only in the upper banana branch is significant. The bursts without oscillations are shown with diamonds.

6. DISCUSSION

We have searched 3 yr of archival RXTE data of the neutron star LMXB and atoll source 4U 1728 – 34 for type I X-ray bursts. We have found 38 bursts, 16 of which show nearly coherent burst brightness oscillations. The presence or absence of the oscillations in the bursts is not well correlated with the persistent flux of the source, but it is very well correlated with the position of the source on the atoll track in the color-color diagram. The oscillations are only present in the bursts that occur when the source is near the island state–banana branch vertex or on the banana branch. It is thought (Hasinger & van der Klis 1989) that the position of the source in the atoll track is determined by the mass accretion rate. If true, then the presence of the burst oscillations is very well correlated with the inferred mass accretion rate, and the lack of any correlation with the persistent X-ray flux is further proof that the persistent flux is not a good measure of the accretion rate of the system.

A similar study for KS 1731 – 260 by Muno et al. (2000), although with fewer bursts (nine bursts, five with oscillations), also found that the burst oscillations are only present in bursts that occur at relatively high mass accretion rates. However, Muno et al. (2000) also report that the bursts of KS 1731 – 260 that have episodes of photospheric radius expansion occur at these high accretion rates and that they all exhibit burst oscillations. Such a correlation
can be excluded for 4U 1728–34. When we considered bursts that exhibit photospheric radius expansion episodes, we discovered a strong anticorrelation with inferred mass accretion rate: bursts with episodes of photospheric radius expansion occur only when the source is at its lowest and intermediate mass accretion rates and not at its highest accretion rates. Also, the presence of oscillations during the bursts is not correlated with the presence of photospheric radius expansion episodes: both bursts with and without oscillations can exhibit periods of photospheric expansion. Yet another difference is that the bursts that occurred during relatively high mass accretion rates were the dimmest in our sample while the bursts in KS 1731–260 were bright when the accretion rate in that system was high (Muno et al. 2000). It is unclear why the positions of bursts in the color-color diagram are very similar with respect to the existence of burst oscillations in both 4U 1728–34 and KS 1731–260 but other burst properties differ so significantly with position in the color-color diagram (and thus with the inferred mass accretion rate).

One clue to these differences may be found in the theory of thermonuclear bursts. Most atoll sources accrete mass at rates in the range $0.01 M_{\text{edd}} < M < 0.3 M_{\text{edd}}$ (Hanawa & Fujimoto 1982; Bildsten 2000; although some Atoll sources can accrete below 0.01 $M$, this regime is not relevant for 4U 1728–34 and KS 1731-260). In this regime, the model of Fujimoto, Hanawa, & Miyaji (1981) for thermonuclear bursts (see also Bildsten 1998) predicts two main behaviors dominated by the accretion rate. At relatively low mass accretion rates, the hydrogen on the neutron star surface burns stably, forming a layer of pure helium. As more matter accumulates, this layer is compressed and heated until it ignites unstably, producing a pure helium burst. As the mass accretion rate increases, hydrogen is accreted faster than it can be burned, and when the helium flash ignites, it does so in a mixed hydrogen/helium environment. For atoll sources, bursts occurring in the island state at low inferred mass accretion rates would then be the result of pure helium flashes, with the fraction of hydrogen fuel increasing as the source progresses toward the banana branch.

Because of the relative timescales for energy release of the reactions involved (the CNO cycle for hydrogen burning is limited by the rate of $\beta$-decay and thus much slower than the triple-alpha process for helium burning), bursts with high fractions of helium are expected to release their energy faster and reach higher peak fluxes. This behavior seems borne out in the bursts from 4U 1728–34. From Table 4 and Figure 3a, we can see that in our AO1 observations the bursts in the extreme island state (bursts 9–12) have higher peak fluxes than the rest of the bursts in that observation set. Similarly, within the AO3 observations the bursts at the lowest $M$ (22–27 and 38) also have the highest peak fluxes among their group. It is natural, then, that episodes of photospheric radius expansion are anticorrelated with mass accretion rate: the lower the $M$, the higher the helium fraction, the faster the energy release, and the brighter the bursts, making it more likely that they will reach the Eddington limit and expand the photosphere.

In the case of KS 1731–260, Muno et al. (2000) argue that the inverse behavior of this source with respect to the theory’s predictions may be explained by considering not the overall mass accretion rate but the rate of mass accretion local to the fuel surface. If the area over which the matter is being accreted increases with mass accretion rate, the local accretion rate may in fact decrease, causing the inverse behavior (Bildsten 2000). The question then becomes, why does the area over which the accreted matter is distributed increase with increased $M$ in KS 1731–260 but not in 4U 1728–34? The answer may lie in the intrinsic differences of the neutron stars in each of these systems. For example, a significant difference in the magnetic field (i.e., its strength and orientation) of the neutron star in 4U 1728–34 compared to that in KS 1731–260 may inhibit the motion of matter from the equator to higher latitudes. Alternatively, if the frequency of the burst oscillations is indeed the true spin frequency of the neutron star, then KS 1731–260 with an asymptotic oscillation frequency of 524 Hz is spinning nearly 45% faster than 4U 1728–34 (with an asymptotic oscillation frequency of 363 Hz). This may reduce the effective gravity at the equator of the neutron star in KS 1731–260 and allow more significant spread of the accreted matter.

If KS 1731–260 and 4U 1728–34 are so different with respect to their burst behavior, why then are burst oscillations not observed at low inferred mass accretion rates in either of these sources? Evidently, the mechanism producing the oscillations is strongly influenced by the overall mass accretion rate of the system. Since the burst oscillations are likely closely tied to the properties of the nuclear burning, it is very possible that we are seeing the direct influence of mass accretion rate on the burning behavior. Muno et al. (2000) point to recent work by Cumming & Bildsten (2000) that indicates that modulations of the burst emission are more likely observable during helium-rich bursts, which they argue occur in the banana branch for KS 1731–260, where the burst oscillations are observed in this source. This cannot be the case for 4U 1728–34 as we have argued that the bursts with oscillations in 4U 1728–34 have in fact high fractions of hydrogen mixed in that causes them to be dim. Further work on possible “hot spot” or other alternative mechanisms for the production of burst oscillations will greatly illuminate this issue.

Although it is likely that a low mass accretion rate directly inhibits the oscillation production mechanism, we explore the possibility that these oscillations are in fact present during the burst but that environmental changes (due to the differences in $M$) cause the oscillations to become undetectable at low $M$. Recently, the X-ray-eclipsing source X 1658–298 was found to also exhibit oscillations during five bursts (Wijnands et al. 2000). Several more bursts were found that did not show these oscillations. However, there is strong evidence that the absence of oscillations in those bursts was caused by environmental changes in the system. In X 1658–298, the oscillations were undetectable or only marginally detectable at times when the source exhibited clear episodes of dipping behavior, making it likely that the mechanism behind the dips causes the oscillations to become undetectable (Wijnands et al. 2000). The dips can be understood as an obscuration of the inner system by matter periodically coming into the line of sight. This same matter, then, also attenuates the oscillations, making them undetectable. Although no X-ray dips have been observed for both 4U 1728–34 and KS 1731–260, it is possible that the absence of burst oscillations at low mass accretion rates in these sources might also be due to changes in the environment. It is known that when $M$ decreases in all atoll sources, the X-ray spectrum
becomes significantly harder and follows a power-law spectrum (see, e.g., Barret et al. 2000 for a recent study of the hard X-ray spectrum of several atoll sources). It has been postulated that this power-law spectrum is due to a Comptonizing medium (e.g., a corona) around the inner system. If such a medium is indeed present at low $M$ but not at high $M$, it might be responsible for smearing out the oscillations, making them unobservable at low $M$. Similar mechanisms have also been introduced to explain the absence of the expected coherent pulsations in the persistent X-ray emission of neutron star LMXBs.

However, this interpretation is not without problems. It has been shown that the only LMXB for which coherent millisecond oscillations have so far been found during the persistent emission (the transient SAX J1808.4 – 3658; Wijnands & van der Klis 1998a) was in the island state (as judged both from the aperiodic rapid variability and the power-law spectrum; Wijnands & van der Klis 1998b; Gilfanov et al. 1998) during the observations that led to its discovery as a millisecond X-ray pulsar. Therefore, if a Comptonizing medium is present in 4U 1728 – 34 and KS 1731 – 260 and it blurs the oscillations during the type I X-ray bursts, why are the pulsations in SAX J1808.4 – 3658 not attenuated? This suggests that the mass accretion rate has a more direct influence on the production mechanism of the burst oscillations.

Such a direct influence of $M$ on the burst oscillations is also suggested by the fact that for seven bursts in 4U 1728 – 34 the oscillations were visible during both the rise and the decay phases of the burst, while seven bursts show oscillations only in the decay phase and two bursts show oscillations during the rise but not during the tail of the burst. We find that in 4U 1728 – 34 bursts with oscillations only during the tail occur at intermediate mass accretion rates while bursts with oscillations in both the rise and the decay occur at high mass accretion rates. Our data further suggest that bursts with oscillations only in the rise occur at the highest mass accretion rates. Clearly, the exact moment when the oscillations will be present during the bursts is determined by the mass accretion rate, which strongly suggests that the burst oscillations are indeed heavily influenced by the mass accretion rate directly and not by an $M$-induced environmental change.

The behavior of the bursts, in particular the burst oscillations, in 4U 1728 – 34 is very rich, and many questions remain for which we have no adequate answers. Although the production mechanism behind the burst oscillations is not well understood, their coherence (Strohmayer & Markwardt 1999; Munro et al. 2000) and their frequency stability over several years (Strohmayer et al. 1998a) strongly suggest that indeed the oscillations are due to the spin frequency of the neutron star. However, it is still difficult to imagine how the oscillations in the tail of bursts are formed. The entire surface of the neutron star is expected to be involved in the thermonuclear flash after the first few seconds. In such an environment a hot spot would probably not survive. A possible solution to this quandary is to invoke a different mechanism to produce the oscillations in the decay phase of bursts. However, burst 17 in our sample (see Fig. 2) shows what appears to be a continuous evolution of the oscillation frequency. This strongly suggests that only one mechanism is behind the burst oscillations.

When we observe the oscillations in the tail of the burst, we usually also see an increase in the frequency by 1–2 Hz as the burst progresses (as reported, for example, by Strohmayer et al. 1996, 1998a and Strohmayer & Markwardt 1999). The observed evolution of the oscillation frequency can be convincingly attributed to the expansion of the neutron star atmosphere and conservation of angular momentum (see § 1). However, for at least one of our bursts (burst 17; see Fig. 2) this increase in frequency is about 3.5 Hz. This would mean that the burning layer must have expanded by almost 50 m. It is not clear if such a large expansion can be accounted for by the expanding layer interpretation, although the expansion can be at least as large as 40 m (Cumming & Bildsten 2000). A further challenge to this interpretation is posed by a possibly different type$^4$ of frequency increase observed in the source X 1658 – 298. There we have observed an increase of 5 Hz (Wijnands et al. 2000), which is even larger than what we have found for 4U 1728 – 34. However, because of the higher frequency of the burst oscillations in X 1658 – 298 ($\sim 567$ Hz) compared to that in 4U 1728 – 34, the burning layer has to have expanded more in 4U 1728 – 34 than in X 1658 – 298 (50 m vs. 40 – 45 m).

When we investigated in detail the integrated strength (as defined in § 3) of the burst oscillations, we found that it is well correlated with inferred mass accretion rate: the oscillations increase in integrated strength when the accretion rate of the system increases. This correlation is more evident within bursts observed only a few weeks apart and becomes less clear for bursts separated in time by several months to years. It is unclear why the correlation is strong on the short term (weeks) but fails to hold on longer timescales (months to years). Whatever the modulation mechanism, it will likely depend on the state of the fuel layers on the neutron star, which may change considerably with long-term trends in the mass accretion rate. If we think of the state of the neutron star surface as determining the moment for the onset of the modulation mechanism, then one can imagine that the overall changes in $M$ over months and years are resurfacing the neutron star and hence the “critical” moment will be reached at slightly different accretion rates on subsequent trips down the atoll track. In other words, if the time-averaged accretion rate has been very low for a long interval of time, the structure of the neutron star surface might be different than when the time-averaged accretion rate was considerably larger.

The influences of the mass accretion rate on the burst oscillation properties strongly suggest that they are indeed manifestations of physical properties of the atoll systems. We would expect that this behavior of the oscillations will also be present in other sources. However, no detailed studies have been performed for the other sources similar to our study of 4U 1728 – 34 and that of KS 1731 – 260 by Munro et al. (2000). It is important to determine whether the same correlation will hold for all the sources that have burst oscillations. However, we can definitely exclude the possibility that all X-ray burst sources will show burst oscillations when they are at high mass accretion rates. For at least two sources (Ser X-1 and 4U 1705 – 44), X-ray bursts have been observed when they were on the banana branch, thus at relatively high mass accretion rates. No burst oscillations were discovered during those bursts (R. Wijnands 2000, private communication; Ford, van der Klis, & Kaaret 2000).

$^4$ The increase in frequency observed in X 1658 – 298 is discontinuous and spectrally soft, neither of which is true for 4U 1728 – 34.
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A more intrinsic reason (e.g., binary inclination, the strength and/or orientation of the magnetic field, the composition of the accreted material) must be found to explain the many burst sources that do not show burst oscillations. On the other hand, it is still possible that a considerable fraction of those sources have indeed only been observed in their island states and might still show burst oscillations when they can be observed to burst in their banana branches.

To conclude, it is clear that from the study of 4U 1728−34 and KS 1731−260 we can already glean some common behaviors and many differences. More atoll systems must be searched for oscillations in their bursts to begin differentiating between those trends that are universal across atoll sources and those that are determined by intrinsic differences of the systems.

Note added in manuscript.—When we were about to submit our paper we became aware of the paper in preparation by van Straaten et al. (2000) presenting a similar analysis of 4U 1728−34. Although their study is limited to the AO1 and AO2 observations, they confirm our main conclusions: the oscillations are only present during bursts at the highest inferred mass accretion rates and the strength of the burst oscillations increases with accretion rate. They distinguish between two types of photospheric radius expansion episodes, those marked by a small increase in radius after the main photospheric radius expansion episode, which they termed unusual, and the more standard continuous radius decrease after the main episode of radius expansion. They find that standard photospheric radius expansion bursts show oscillations only after the peak of the burst and unusual episodes of photospheric radius expansion occur only in bursts at the lowest M. We note that these two correlations also hold when including our AO3 data set.

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