THE LOW-MASS X-RAY BINARY X1832–330 IN THE GLOBULAR CLUSTER NGC 6652: A SERENDIPITOUS ASCA OBSERVATION
KOHI MUKAI\textsuperscript{1} AND ALAN P. SMALE\textsuperscript{1}
Code 662, NASA/Goddard Space Flight Center, Greenbelt, MD 20771
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ABSTRACT
The low-mass X-ray binary (LMXB) X1832–330 in NGC 6652 is one of 12 bright, or transient, X-ray sources to have been discovered in globular clusters. We report on a serendipitous ASCA observation of this globular cluster LMXB, during which a type I burst was detected and the persistent, nonburst emission of the source was at its brightest level recorded to date. No orbital modulation was detected, which argues against a high inclination for the X1832–330 system. The spectrum of the persistent emission can be fitted with a power law plus a partial covering absorber, although other models are not ruled out. Our time-resolved spectral analysis through the burst shows, for the first time, clear evidence for spectral cooling from $kT = 2.4 \pm 0.6$ keV to $kT = 1.0 \pm 0.1$ keV during the decay. The measured peak flux during the burst is $\sim 10\%$ of the Eddington luminosity for a 1.4 $M_\odot$ neutron star. These quantities are characteristic of a type I burst, in the context of the relatively low quiescent luminosity of X1832–330.

Subject headings: binaries: close — X-rays: bursts — X-rays: stars

1. INTRODUCTION
Of the $\sim 150$ globular clusters associated with the Milky Way, 12 have been seen to harbor a bright ($L_x > 10^{36}$ ergs s$^{-1}$), or transient, low-mass X-ray binary (LMXB) (van Paradijs 1995). These binaries presumably are formed through stellar encounters in the dense cores of the clusters; such events play an important role in the dynamical evolution of the clusters, as the formation of a single LMXB can impart enough kinetic energy to the surrounding stars to terminate a core collapse. At the same time, the globular cluster LMXBs provide a unique opportunity to study LMXBs at a well-known distance with a well-known (and usually very poor) metallicity level.

The X-ray source X1832–330 in the globular cluster NGC 6652 is a lesser known example of this class. Although the error box for the HEAO 1 source, H1825–331, contained this cluster, it was originally not considered to be a secure identification because the error box covered a 2.7 deg$^2$ area in Sagittarius (Hertz & Wood 1985). The first secure detection of X1832–330 as a globular cluster LMXB was made during the course of the ROSAT all-sky survey (Predehl, Haslinger, & Verbunt 1991). More recently, it was detected in pointed ROSAT observations (Johnston, Verbunt, & Haslinger 1996), and two type I X-ray bursts from this source, as well as the persistent emission, have been detected using the Wide-Field Camera of the BeppoSAX satellite (in't Zand et al. 1998). Thus, there is now strong circumstantial evidence that the HEAO 1 source H1825–331 and X1832–330 are the same source; here we have adopted this identification as a working assumption.

In the above-mentioned papers, the distance to X1832–330 was assumed to be $\sim 14.3$ kpc. However, the first published color-magnitude diagram of this cluster (Ortolani, Bica, & Barbuy 1994) has led to the reevaluation of the distance to $\sim 9.3$ kpc, based on the measured $V$ magnitudes $V_{\text{H}} = 15.85 \pm 0.04$ of its horizontal branch (as well as the interstellar reddening, $E_{(B-V)} = 0.10 \pm 0.02$). Moreover, NGC 6652 appears to be significantly younger than the average globular clusters (Chaboyer, Demarque, & Sarajedini 1996). Thus, the LMXB X1832–330 in NGC 6652 may provide an important comparison with other globular cluster sources because of the relative youth and the relatively high metal content ([Fe/H] = −0.96) of this cluster (though it is not the highest among globular clusters with LMXBs).

A search for the optical counterpart has recently been carried out using new ground-based data along with archival Hubble Space Telescope (HST) data (Deutsch, Margon, & Anderson 1998). Although the archival HST observations do not completely cover the X-ray error circle, the most promising candidate for the optical counterpart is their star 49, which is relatively faint ($M_B = +5.5$) compared with those of other globular cluster LMXBs.

In this paper, we present our analysis of a serendipitous ASCA observation of X1832–330; in comparing the previous observations with the ASCA data, we have recalculated the previously published source luminosities for a new fiducial distance of 9.3 kpc.

2. OBSERVATION
The region of the sky containing NGC 6652 was observed with the Japanese X-ray satellite ASCA (Tanaka, Inoue, & Holt 1994) between 1996 April 6 20:12 UT and April 7 19:00 UT (sequence number 54016000). This observation was part of a program to observe diffuse Galactic emission and only serendipitously included X1832–330 in its field of view. There are four co-aligned X-ray telescopes (XRTs) on board ASCA, two with SIS (solid-state imaging spectrometer, using CCDs) detectors and two with GIS (gas-imaging spectrometer) detectors. However, little useful data were taken with GIS-2 because of a problem with its onboard processor.\footnote{\textsuperscript{2} This problem had been noticed during the ground contact around 1996 April 5 20 UT, but an initial attempt to fix it was unsuccessful. After the software was reloaded, the CPU returned to normal status at April 7 18:12 UT. There are, therefore, $\sim 40$ minutes of useful GIS-2 data, which we have chosen not to analyze.}

No such problems exist for the SIS data; however, the observation was done with both SIS detectors in 4-CCD
mode, with X1832 – 330 near the center of the field of view. This pointing direction minimizes the vignetting, but the photons from X1832 – 330 are spread over all four chips, complicating the analysis. Moreover, 4-CCD observations suffer most severely from the cumulative effect of radiation damage. As a consequence, events below ~0.7 keV had to be discarded on board to avoid telemetry saturation due to flickering pixels, and the spectral resolution and the quantum efficiency are both severely degraded (Dotani et al. 1995). The degradation is believed to be due largely to residual dark distribution (RDD): a significant fraction of the CCD pixels now show elevated levels of dark current, the histogram of which is strongly skewed. When RDD-affected data are processed (on board or on the ground) assuming a Gaussian distribution of dark current, this leads to incorrect pulse heights or spurious rejection of X-ray events as particle events. The current version of the response generator has a model of the degrading spectral resolution but not one of the degrading quantum efficiency. We have used the FTOOL, “correctrdd,” which partially recovers the detection efficiency; however, this algorithm is not 100% effective. Moreover, the calibration of RDD-corrected data is uncertain. Therefore, we have primarily relied on the GIS data, cross-calibrated the RDD-corrected SIS data against the GIS data, and used the SIS data only when GIS data were unavailable.

Since a bright source is clearly detected (see below), we have opted to use loose sets of screening criteria. For the GIS, we use non–South Atlantic Anomaly (non-SAA), non–Earth-occulted (ELV > 5°) data at the standard high-voltage setting and exclude only regions in which the cutoff rigidity is less than 4 GeV c⁻¹; note that, for safety reasons, the high voltage is reduced well before the satellite enters the SAA. After screening, we are left with ~42 ks of good GIS-3 data.

For the SIS, we use additional criteria that the line of sight must be more than 20° away from the sunlit Earth, the time after day/night and SAA transitions must be greater than 128 s, and the PIXL monitor counts for the CCD chips must be within 3 σ of their mean value. Moreover, we have imposed the condition that the data must have been taken in the faint mode. To correct for RDD and DFE (dark frame error, the variation in the mean dark level of all the pixels due primarily to scattered light on the CCD), we have applied “faintdfe” to the original faint mode data first, followed by “correctrdd,” before converting to Bright2 mode, to minimize the interference between DFE and RDD corrections. This resulted in ~21 ks of good SIS data.

We have tested the calibration of RDD-corrected SIS data by performing simultaneous fits to the GIS-3 and SIS data. We find that, even after the RDD correction, the best-fit SIS model contains a spurious excess of $1.6 \times 10^{21}$ cm⁻² as well as a normalization below that of the GIS-3 data by a factor of 1.17.

3. RESULTS

3.1. GIS-3 Data

In Figure 1, we have plotted the background-subtracted light curve of X1832 – 330 in 128 s bins. The source appears variable on short timescales (from about a few bins of this diagram down to 4 s): a straight line fit to a 4 s bin light curve, after removing the longer term trend (by subtracting a 256 s running average of itself), yields a $\chi^2$ of 1.114 for 10,479 degrees of freedom, meaning that the source is variable at a formal confidence level of $1 - (1 \times 10^{-15})$.
However, some caution is required at this level: although background is negligible, there may be systematic contribution to this apparent variability from, e.g., attitude jitter or the imperfect correction of the time-dependent detector gain. Moreover, a Fourier transform did not reveal a periodicity in the range 8 s to ~1 hr (with an rms amplitude of ~0.5% in this range); the highest peaks in the periodogram in this range have semiamplitudes of 1.6%, while a signal would have to have an amplitude of greater than 2% to be detected at greater than 99% confidence.

Although there are some possible peaks in the periodogram at longer periods, we consider these to be rather unreliable since they can be explained as due to an interplay of the quasi-regular data gaps and the increased count rate between 0 and 2 UT on April 7 (see Fig. 1); this flareslike event may well be part of the aperiodic variability. We do not see spectral changes during this flareslike event (such as might be expected were it the tail of a type I burst). The highest peaks in the periodogram at 8 s and at 17,400 s (2.8%). Although non-sinusoidal modulation (e.g., dipping activities) with certain periods (e.g., near the 96 minute spacecraft orbit) may have eluded detection, this would seem to require an unfortunate coincidence.

In Figure 2a, we present the average GIS-3 spectrum of X1832—330 with the best-fit power-law model. The fit is poor, with $\chi^2 = 1.81$; the parameters are photon index $\alpha = 1.75 \pm 0.01$ and $N_H = (3.6^{+0.2}_{-0.3} \times 10^{21})$ cm$^{-2}$ and a 2-8 keV flux of $1.54\times10^{-10}$ ergs cm$^{-2}$ s$^{-1}$. Note that the fitted $N_H$ is considerably greater than that estimated from the optical extinction ($\sim5\times10^{20}$ cm$^{-2}$) and the value derived from the ROSAT Position Sensitive Proportional Counter (PSPC) spectral fit ($6.7^{+0.2}_{-0.2} \times 10^{20}$ cm$^{-2}$; see also the bottom panel of Fig. 2a). Moreover, the inferred photon index $\alpha$ is radically different between the ASCA GIS (1.75) and ROSAT PSPC (1.07) observations. We therefore must conclude that the spectrum of X1832—330 is highly variable, more complex than a simple power law, or both.

For a likely candidate for the complex spectral shape, we have tried a power law modified by a partial covering absorber (with a fixed interstellar absorption of $\sim5\times10^{20}$ cm$^{-2}$) to the GIS-3 data. This has markedly improved the fit (to $\chi^2 = 1.15$; $\alpha = 1.86^{+0.03}_{-0.02}$, with ~67% covering by a $N_H = 7.6 \pm 0.9 \times 10^{21}$ cm$^{-2}$ absorber). Moreover, this model provides a plausible description of the spectrum in a simultaneous fit to the ASCA GIS and ROSAT PSPC spectra (Fig. 2b). We therefore conclude that the X-ray spectrum of X1832—330 is not a simple power law. However, given the energy range of the data and the current level of calibration uncertainties, we cannot say for sure if this description of the spectral shape is unique or preferred.

In Table 1, we have summarized the long-term history of the X-ray luminosity of X1832—330.

### 3.2. SIS Data

For the time intervals when both GIS-3 and the SIS instruments were taking data, the latter add little. However, we have discovered a type I X-ray burst from X1832—330 in the section of SIS data for which there is no GIS-3 coverage. The light curves in three energy bands are shown in Figure 3a. The reason this burst was not covered by the GIS-3 data is that this happened just before ASCA went into the SAA; the high voltage level of the GIS had already been reduced as a precaution. This segment of data ends when the SIS also stopped taking data, as ASCA approached the SAA. We have therefore examined the housekeeping as well as scientific data carefully to ascertain whether this event could be an instrumental artifact. However, the radiation belt monitor counts indicate that the particle background was less than 10 counts s$^{-1}$, i.e., at a quiescent (non-SAA) level (all data with monitor rates up to 500 counts s$^{-1}$ have routinely been included in GIS data analysis, with no obvious ill effects). The monitor rate exceeded 1000 counts s$^{-1}$ ~200 s after the end of the SIS data (in contrast, the radiation belt monitor rates exceed 10,000 in the heart of the SAA).

The longer duration at lower energies, shown in Figure 3a, is what is expected in a type I X-ray burst as the neutron star cools. To further investigate the spectral evolution, we have performed spectral fitting of the four time intervals indicated in Figure 3a. We have used the combined SIS-0/SIS-1 data and the quiescent SIS spectrum as the background. We present the results of blackbody fits in Figure 3b. For interval 1, we find that a significant $N_H$ is required in order to fit the data adequately; for the other intervals, the fitted $N_H$ values are consistent with the interstellar $N_H$ ($\sim5\times10^{20}$ cm$^{-2}$) once the systematic offset of $1.6 \times 10^{21}$ cm$^{-2}$ (see §2) has been taken into account.

As is typical of type I bursts, the color temperature shows a significant decline during the decay of the burst. The inferred radius of the blackbody emitter (we have used the distance of 9.3 kpc and included the normalization correction factor of 1.17) also shows behavior typical of type I bursts, although it may be on the small side. The inferred bolometric flux during interval 1 is $2.03 \times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$; thus, the bolometric luminosity is $2.1 \times 10^{37}$ ergs s$^{-1}$. This may underestimate the true peak flux/luminosity somewhat, because of the limited time resolution of our

### Table 1

| Epoch          | Instrument | 2–8 keV Flux* | 2–8 keV Luminosity* |
|---------------|------------|---------------|---------------------|
| 1977–1978     | HEAO 1 A1  | $8.3 \times 10^{-12}$ | $8.6 \times 10^{34}$ |
| 1992 Apr      | ROSAT PSPC | $1.16 \times 10^{-10}$ | $1.2 \times 10^{36}$ |
| 1996 Apr      | ASCA GIS   | $1.54 \times 10^{-10}$ | $1.6 \times 10^{36}$ |
| 1996 and 1997 | BeppoSAX WFC | $5.4 \times 10^{-11}$ | $5.6 \times 10^{35}$ |

* Measured or inferred flux in the 2–8 keV band, in ergs cm$^{-2}$ s$^{-1}$.

b Inferred 2–8 keV luminosity in ergs s$^{-1}$ for an assumed distance of 9.3 kpc.

c Source identification remains tentative.
4. DISCUSSION

The quiescent X-ray spectrum of X1832—330 appears to have a complex shape. A pointed X-ray observation of X1832—330 with a wide spectral coverage appears worthwhile: if the complex shape is indeed due to a partial covering absorber, we then need to understand where it could be located, particularly if X1832—330 is a low-inclination system.
We have observed a type I X-ray burst; although this is not the first from this system to be reported (in't Zand et al. 1998), ours is the first time-resolved spectral analysis of a burst from X1832–330. The spectral cooling we observe is typical of type I bursts and can be considered the definitive evidence that X1832–330 is a neutron star binary. The burst appeared to have peaked at $\sim 10\%$ Eddington luminosity but with a typical total fluence. We have approximately 160 s of data after the onset of the burst, and X1832–330 clearly had not completed its return to the quiescent state by the end of this data segment; the duration $\tau$ was about 70 s. While this duration is relatively long among all X-ray bursts, it is actually typical of systems with low persistent luminosities ($\gamma$, the ratio of persistent flux to Eddington luminosity, is about $1\%$ for X1832–330): $\tau$ ranges from 30 s to a few minutes at $\log \gamma \sim -2$ (van Paradijs, Pennix, & Lewin 1988). We conclude that the ASCA burst was a typical type I event.

Deutsch et al. (1998) have recently suggested a relatively faint star, star 49, as a possible optical counterpart. This faintness may be intrinsic or geometric: since most of the optical light from an LMXB is due to reprocessing in the nearly flat accretion disk, a high binary inclination can lead to an apparently faint optical counterpart. We can comment on this possibility, as the GIS-3 light curve probably is the most suitable X-ray data for orbital period search ever obtained for X1832–330. Since we do not detect orbital modulations, such as eclipses, dips, or quasi-sinusoidal modulations, we conclude that X1832–330 is unlikely to be a high-inclination system.

X1832–330 was seen at X-ray luminosity levels ($\sim 10^{36}$ erg s$^{-1}$) typical of X-ray bursters during the ROSAT and ASCA observations. This lends additional support against X1832–330 being a high-inclination, accretion disk corona source. Moreover, we (as well as in't Zand et al. 1998) observed what appears to be a typical type I X-ray burst, suggesting that we do directly observe the neutron star in X1832–330. These provide additional arguments against X1832–330 being a high-inclination system.

If this LMXB is at a low inclination, then a natural explanation for the optical faintness would be that it is ultracompact, perhaps similar to X1820–303 in NGC 6624 (Anderson et al. 1997). Since optical luminosity is dominated by reprocessing, smaller systems tend to be optically fainter. We consider this to be circumstantial evidence for X1832–330 being an ultracompact binary, joining those in NGC 6624, NGC 6712, and perhaps NGC 1851 (Stella, White, & Priedhorsky 1987; Homer et al. 1996; Deutsch et al. 1996).
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