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A *CHANDRA* OBSERVATION OF THE GLOBULAR CLUSTER TERZAN 1: THE NEUTRON STAR X-RAY TRANSIENT X1732−304 IN QUIESCENCE

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ABSTRACT

We present a short (∼3.6 ks) *Chandra*/HRC-I observation of the globular cluster Terzan 1. This cluster is known to contain the bright neutron star low-mass X-ray binary X1732−304, which was active during the 1980s and most of the 1990s. But a *BeppoSAX* observation performed in 1999 only showed a very weak source, indicating that the source had become quiescent. During our *Chandra* observation, we detect one source with a 0.5–10 keV luminosity of approximately $(1–2) \times 10^{33}$ ergs s^{-1} (for an assumed distance of 5.2 kpc). However, its position is not consistent with that of X1732−304. We do not conclusively detect X1732−304 with a 0.5–10 keV luminosity upper limit of $(0.5–1) \times 10^{33}$ ergs s^{-1}. This limit is consistent with the luminosities observed for several neutron star X-ray transients in our Galaxy when they are quiescent, strongly suggesting that X1732−304 was still quiescent during our *Chandra* observation. If the quiescent emission in neutron star X-ray transients is due to the thermal emission from the neutron star, then it is expected that the quiescent luminosity depends on the time-averaged accretion rate of the source. However, the upper limit on the quiescent luminosity of X1732−304, combined with its very long accretion episode prior to the current quiescent episode, indicates that the quiescent episodes of the source have to be longer than ∼200 yr. This would be the second system after KS 1731−260 for which quiescent episodes longer than several hundreds of years have been inferred. We discuss this possibility and alternative quiescent models to explain our results.

Subject headings: accretion, accretion disks — stars: individual (X 1732−304) — X-rays: stars

1. INTRODUCTION

In 1980, *Hakucho* detected a bursting X-ray source in the direction of the globular cluster Terzan 1 (Makishima et al. 1981; Inoue et al. 1981). Several years later, a steady X-ray source was detected (X1732−304) consistent with this globular cluster and it is most likely the same source as the bursting source (Skinner et al. 1987; Parmar, Stella, & Giommi 1989). Since then, the source has persistently been detected at 2–10 keV luminosities between a few times 10^{35} ergs s^{-1} and $\sim 10^{37}$ ergs s^{-1} (see Fig. 3 of Guainazzi, Parmar, & Oosterbroek 1999 and references therein). The source was detected with the *ROSAT* high-resolution imager, which constrained the position of the source to ∼5″ (Johnston, Verbunt, & Hasinger 1995). Also, a radio source was detected with the *VLA* in the *ROSAT* error circles (Martí et al. 1998) and it might be the radio counterpart of X1732−304.

Guainazzi et al. (1999) reported on an anomalous low-state from X1732−304 during a 1999 *BeppoSAX* observation. They could only detect one dim source with a 2–10 keV luminosity of 1.9×10^{33} ergs s^{-1} (for a distance of 5.2 kpc [Ortolani et al. 1999]; note that Guainazzi et al. 1999 used 4.5 kpc). This source luminosity and its X-ray spectrum are both very similar to those observed for the neutron star transients in the Galaxy when they are in their quiescent state. These similarities strongly indicate that X1732−304 suddenly turned off and became quiescent after having accreted for more than 12 yr. This conclusion also holds when this *BeppoSAX* source is not X1732−304 but an unrelated source, likely also part of the globular cluster (Guainazzi et al. 1999). The long active episode of X1732−304 makes it very similar to the neutron star X-ray transient KS 1731−260, which was also active for more than a decade (see Wijnands et al. 2001, who called such systems long-duration X-ray transients).

Recently, it was realized (Wijnands et al. 2001) that when such long-duration X-ray transients turn off again, they could be used to study the effects of a prolonged period of accretion on the neutron star core and crust and on the quiescent properties of neutron star X-ray transients. At the end of 2000 or early 2001, KS 1731−260 suddenly turned off after an accretion episode which lasted for at least 12 yr. A *Chandra* observation on this source performed in 2001 March (just a few months after this source turned off) showed that the quiescent luminosity and temperature of this source were very similar to those of the ordinary transients in quiescence (Wijnands et al. 2001). The *BeppoSAX* observation of KS 1731−260, which was performed a few weeks before the *Chandra* one, showed very similar source properties (Burderi et al. 2002). If the quiescent emission in neutron star transients is due to thermal emission from the neutron star (e.g., van Paradijs et al. 1987), then the exact quiescent luminosity should depend on the time-averaged accretion rate of the system (e.g., Campana et al. 1998; Brown, Bildsten, & Rutledge 1998). If true, then KS 1731−260 has to be in quiescence in between outbursts for over a thousand years in order for the neutron star to be as cool as measured (Wijnands et al. 2001; Rutledge et al. 2002).

It is unclear if KS 1731−260 is unique in its behavior or whether other sources behave similarly. Several more long-duration transients are known and among them,

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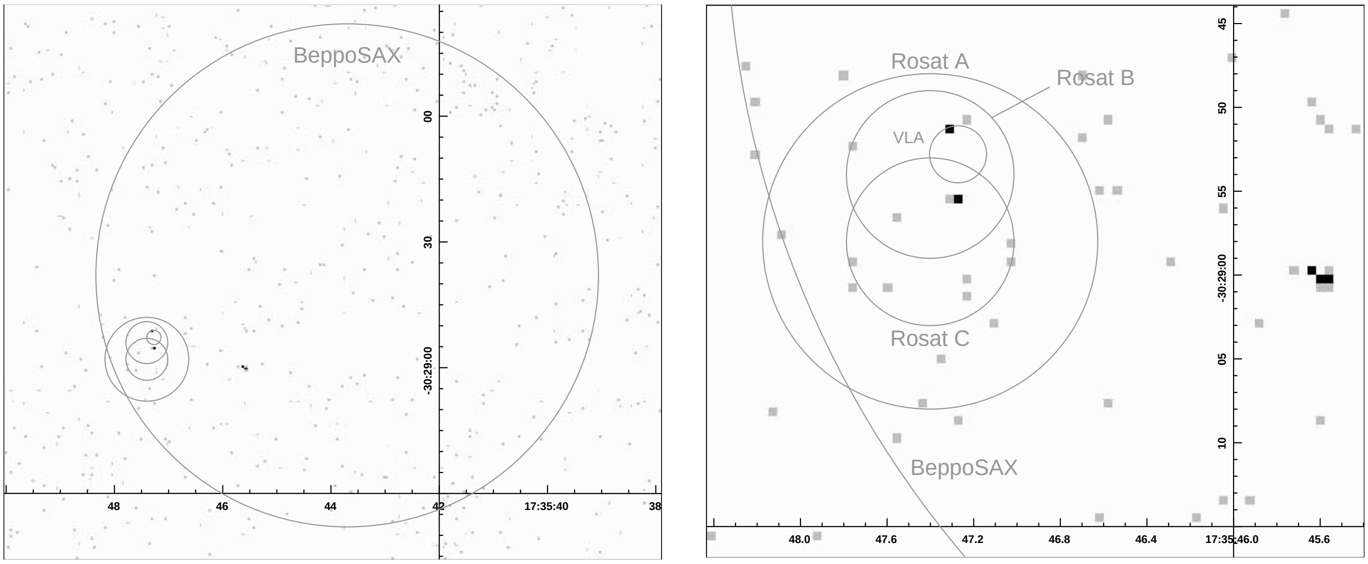

FIG. 1.—*Chandra*/HRC-I image of the field of Terzan 1, with a bin size of 0″.5. *Left*: Field covering the total *BeppoSAX* error circle (using a radius of 1′; Guainazzi et al. 1999). *Right*: Close-up of the field covering the *ROSAT* error circles. (See Johnston et al. 1995 for the three *ROSAT* pointings and the lettering of the observations.) Also shown is the error circle of the radio source detected with the *VLA* (Martí et al. 1998).

X1732−304 is one of the best candidates to study in quiescence and to compare with KS 1731−260, because it is currently quiescent. Here we report our analysis of a short *Chandra* observation on this source during quiescence.

2. OBSERVATION, ANALYSIS, AND RESULTS

The *Chandra* observation used in this paper was performed on 2000 March 9 for a total of 3665 seconds of on-source time using the HRC-I instrument.[4] The central part of the obtained image is displayed in Figure 1. In the left panel, the field of the *BeppoSAX* error circle is shown (Guainazzi et al. 1999), and in the right panel, a close-up of the *ROSAT* and *VLA* error circles (Johnston et al. 1995; Martí et al. 1998) is shown. In the HRC-I field containing the *BeppoSAX* error circle, only one source was detected using the tool WAVDETECT. The position of this source, as determined with this tool (R.A. = $17^{\rm h}35^{\rm m}45^{\rm s}.603$, decl. = $-30°29'00''.1$. All coordinates in this paper are for J2000.0; the error on the position is dominated by the pointing accuracy of the satellite and is typically 0″.6, 1 σ; Aldcroft et al. 2000), is inconsistent with that of the *ROSAT* and *VLA* positions of X1732−304 (Fig. 1). Therefore, this source cannot be the quiescent X-ray counterpart of X1732−304; we designate this source CXOGLB J173545.6−302900. We used the tool DMEXTRACT to extract the number of source counts in a 3″ circle around the source position. The number of background counts was estimated by using an annulus from 3 to 10″ around the same position. In total, we detected only 11 counts from the source position, and according to DMEXTRACT, about 1 count is most likely due to background. The resulting source count rate is 2.8×10^{-3} counts s^{-1}. Due to this low count rate and the limited spectral resolution of the HRC-I, the spectrum of the source cannot be constrained. We used PIMMS in order to convert the count rate to a flux by assuming a column density of 1.8×10^{22} cm^{-2} (as determined for Terzan 1 [Johnston et al. 1995] and assuming the source is located in this cluster) and different spectral shapes. For a blackbody spectrum with kT of 0.2–0.3 keV, the unabsorbed 0.5–10 keV flux is (3–7) $\times 10^{-13}$ ergs cm^{-2} s^{-1} (resulting in a luminosity of (1–2) $\times 10^{33}$ ergs s^{-1} for a distance of 5.2 kpc), and for a power-law spectrum with a photon index of 2, the flux would be 4.0×10^{-13} ergs cm^{-2} s^{-1} (1.3×10^{33} ergs s^{-1}). The possible optical identification of this source and its nature will be further discussed by S. Cody et al. (2002, in preparation).

When using WAVDETECT, no source is detected in the *ROSAT* or *VLA* error circles of X1732−304. However, when visually inspecting the region of the *ROSAT* error circles (Fig. 1, *right*), two possible sources are suggested by the data; one with 3 counts (at R.A. = $17^{\rm h}35^{\rm m}47^{\rm s}.272$, decl. = $-30°28'55''.5$, error $\sim$1″) and one with only 2 counts (at R.A. = $17^{\rm h}35^{\rm m}47^{\rm s}.313$, decl. = $-30°28'51''.3$, error $\sim$1″). However, the detection of either source is statistically not significant and those sources could be due to chance superposition of background photons. Longer *Chandra* observations are needed to confirm the presence of both sources. If the presence of those sources can be confirmed, then their positions are consistent (within the *Chandra* pointing errors) with the *ROSAT* and *VLA* positions of X1732−304. However, for now, we assume that we did not detect X1732−304 and that fewer than 5 counts have been observed from it, resulting in a count rate upper limit of 1.4×10^{-3} counts s^{-1}. By assuming that the quiescent spectrum of this source is very similar to that of the other quiescent neutron star transient, we converted this count rate limit into a flux upper limit using PIMMS. For a blackbody shaped spectrum with kT of 0.2–0.3 keV and a column density of 1.8×10^{22} cm^{-2}, the unabsorbed 0.5–10 keV flux upper limit would be (1.6–3.5) $\times 10^{-13}$ ergs cm^{-2} s^{-1}.

Using our new *Chandra* result on X1732−304, we can look back at the *BeppoSAX* observation of Terzan 1 in order to investigate whether the *BeppoSAX* source is X1732−304 or an unrelated source. We converted (using

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[4] We used the CIAO tools and the threads listed at http://www.asc.harvard.edu to analyze the data.

PIMMS) the *BeppoSAX* LECS and MECS count rates listed by Guainazzi et al. (1999) into predicted *Chandra*/HRC-I count rates using a column density of 1.8×10^{22} cm^{-2} and the power-law shaped spectrum observed (with photon index of 2.2 ± 0.6; Guainazzi et al. 1999). The predicted HRC-I count rate is in the range $(3\text{–}9) \times 10^{-3}$ counts s^{-1}, which is consistent with the count rates observed for the 10 count source combined with the count rate upper limit on X1732−304. Therefore, no strong evidence is available for variability between the *BeppoSAX* and *Chandra* observations. However, X1732−304 is currently not the brightest X-ray source in the cluster, indicating that most, if not all, of the flux detected by *BeppoSAX* might not have come from this source but from the 10 count source we discovered.

The current quiescent state of X1732−304 allows for the possible radio identification to be verified and a search for the optical counterpart of the source. The radio and optical observations reported by Martí et al. (1998) and Ortolani et al. (1999) were performed during times when X1732−304 was still actively accreting. The current lack of significant accretion in this system will have most likely also considerably reduced its radio and optical emission.

3. DISCUSSION

We presented a short *Chandra*/HRC-I observation of the globular cluster Terzan 1, known to contain the bright neutron star low-mass X-ray binary X1732−304. Although we detect one source with a 0.5–10 keV luminosity of $(1\text{–}2) \times 10^{33}$ ergs s^{-1}, we could not detect X1732−304 conclusively with a luminosity upper limit of $(0.5\text{–}1) \times 10^{33}$ ergs s^{-1} (0.5–10 keV; for a blackbody shaped spectrum with kT, is 0.2–0.3 keV). Brown et al. (1998) argued that the quiescent emission of neutron star systems is due to thermal emission from the neutron star surface and that the X-ray spectrum should be fitted with a neutron star atmosphere model and not a blackbody. Rutledge et al. (1999) showed that indeed such models can fit the quiescent data, and that the bolometric luminosity obtained is about twice the 0.5–10 keV luminosity. Therefore, we assume a bolometric flux upper limit of $(3\text{–}7) \times 10^{-13}$ ergs cm^{-2} s^{-1} ($[1\text{–}2] \times 10^{33}$ ergs s^{-1}) for X1732−304.

Brown et al. (1998) further argued that if the quiescent luminosity should depend on the time-averaged accretion rate of the source, then a distance-independent relation can be derived between the time-averaged flux $\langle F \rangle$ and the quiescent flux F_q of $F_q \approx \langle F \rangle/135$ (see, e.g., Rutledge et al. 2002; but neglecting neutrino emission from the core). The latter can be rewritten as $\langle F \rangle = t_o \langle F_o \rangle/(t_o + t_q)$ resulting in $F_q \approx t_o/\left(t_o + t_q\right) \times \langle F_o \rangle/135$, with $\langle F_o \rangle$ the average flux during outburst, t_o the average time the source is in outburst, and t_q the average time the source is in quiescence (see also Wijnands et al. 2001). We can estimate $\langle F_o \rangle$ via Figure 3 of Guainazzi et al. (1998), from which it can be deduced that the average 2–10 keV outburst luminosity is around 10^{36} ergs s^{-1}. Due to the relatively high column density toward Terzan 1, the average bolometric luminosity can easily be a factor of 5 or more higher. (PIMMS indeed gives a factor of ∼5 difference between the 2–10 keV absorbed flux and the bolometric unabsorbed flux, using the column density toward Terzan 1 and a power-law spectrum with photon index of 2.) Therefore, we assume a bolometric luminosity of 5×10^{36} ergs s^{-1}, resulting in a bolometric flux $\langle F_o \rangle$ of 1.5×10^{-9} ergs cm^{-2} s^{-1}. By using F_q of $< 7 \times 10^{-13}$ ergs cm^{-2} s^{-1} and a t_o of 12 yr, then the t_q is >180 yr.

We stress that this derived lower limit is subject to large errors because of the uncertainties in the numbers used. For example, we have assumed an outburst duration of 12 yr for the last outburst. However, this should be considered a lower limit because although persistent emission from X1732−304 was only first detected in the mid-1980s (Skinner et al. 1987; Parmar et al. 1989), the source was already detected through X-ray bursts in 1980 with *Hakucho* (Makishima et al. 1981; Inoue et al. 1981), indicating that the source was already actively accreting during that period. When assuming that t_o is more like 17 yr, then t_q would be >250 yr. We have also assumed that the averaged flux during outburst and the duration of the outburst are very similar between distinct outbursts. For X1732−304, we cannot test those assumptions because so far only one outburst has been observed from this source. From other recurrent transients, it is clear that arguments in favor of and against those assumptions can be made, so for simplicity, we assume that it is true for X1732−304. Further (i.e., longer) *Chandra* observations are also needed to determine the exact quiescent luminosity of X1732−304 (including its quiescent spectrum) to constrain further the time the source is inferred to be quiescent.

Assuming that all the above mentioned assumptions are valid, then X1732−304 would be the second system after KS 1731−260 (Wijnands et al. 2001) that has been identified as possibly having rather long quiescent episodes. Remarkably, both systems have very long accretion episodes and long inferred quiescent episodes. (Note that this might also be true for the long-duration transient 4U 2129+47; Wijnands 2002; Nowak, Heinz, & Begelman 2002). In contrast, the ordinary transients which have been detected in quiescence have short outburst episodes and relatively short quiescent ones (see, e.g., Chen, Shrader, & Livio 1997 for the behavior of ordinary transients). This division into two groups is suggestive of the presence of a correlation between the duration of the active episode and that of the quiescent one. It is unclear if such a correlation can be explained in the current disk instability models (e.g., Lasota 2001).

One possible explanation for this apparent correlation might be that in the long-duration transients, enhanced neutrino cooling occurs in the core of their neutron stars, and in the ordinary transients, only standard cooling occurs. Colpi et al. (2001) suggested that when the neutron star mass exceeds 1.65 $M_{\odot}$, this enhanced cooling occurs in the core. If both types of transient systems have similar quiescent episodes, the significantly higher time-averaged accretion rate in the long-duration systems compared to the ordinary ones will increase the mass of the neutron stars in the long-duration transients faster than those in the normal ones. If one assumes that the systems are roughly of equal age, then the long-duration transients will have neutron stars with higher masses and thus are more likely to have enhanced neutrino emission in their neutron star cores.

Alternatively, the quiescent emission might not originate from the neutron star surface but might be due to some other process, such as residual accretion or models in which the neutron star magnetic field is highly involved (e.g., Stella et al. 1994; Menou et al. 1999; Campana & Stella 2000). As already discussed by Wijnands (2002), in such models it is expected that, regardless of the outburst histories, the quiescent emission of the different systems should be very similar if their system parameters (i.e., orbital period, spin, mass, and magnetic field strength of the neutron star) are very similar. Such assumptions are not unrealistic: from the burst oscillations during type I X-ray bursts, we have a good handle on the spin frequency of the neutron star in several normal transients such as Aql X-1 (549 Hz; Zhang et al. 1998) and 4U 1608−52 (619 Hz; Chakrabarty et al. 2000) and in the long-duration transients KS 1731−260 (524 Hz; Smith, Morgan, & Bradt 1997) and MXB 1659−298 (567 Hz; Wijnands, Strohmayer, & Franco 2001), which are all in a very narrow range. Moreover, the orbital periods of Aql X-1 (19 hr; Welsh, Robinson, & Young 2000) and 4U 1608−52 (12.9 hr; Wachter et al. 2002) are not extremely different from that of MXB 1659−298 (7.1 hr; Cominsky & Wood 1984), which indicate similar mass transfer rates from the companion star (see Narayan, Garcia, & McClintock 2001 for a discussion). Therefore, in those alternative models, it is natural to expect that the quiescent properties are very similar among the different type of systems. The small differences in exact luminosity can easily be explained by invoking the small difference in, e.g., the amount of residual accretion or the actual strength of the magnetic field.

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