A CHANDRA OBSERVATION OF THE NEUTRON STAR X-RAY TRANSIENT AND ECLIPSING BINARY MXB 1659–29 IN QUIESCENCE

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Abstract

After almost 2.5 yr of actively accreting, the neutron star X-ray transient and eclipsing binary MXB 1659–29 returned to quiescence in 2001 September. We report on a Chandra observation of this source taken a little over a month after this transition. The source was detected at an unabsorbed 0.5–10 keV flux of only \((2.7–3.6) \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}\), which implies a 0.5–10 keV X-ray luminosity of approximately \((3.2–4.3) \times 10^{33} (d/10 \text{ kpc})^2 \text{ ergs s}^{-1}\), with \(d\) the distance to the source in kiloparsecs. Its spectrum had a thermal shape and could be well fitted by either a blackbody with a temperature \(kT\) of \(\sim 0.3 \text{ keV}\) or a neutron star atmosphere model with a \(kT\) of \(\sim 0.1 \text{ keV}\). The luminosity and spectral shape of MXB 1659–29 are very similar to those observed of the other neutron star X-ray transients when they are in their quiescent state. The source was variable during our observation, exhibiting a complete eclipse of the inner part of the system by the companion star. Dipping behavior was observed before the eclipse, likely due to obscuration by an extended feature in the outer part of a residual accretion disk. We discuss our observation in the context of the cooling neutron star model proposed to explain the quiescent properties of neutron star X-ray transients.

Subject headings: accretion, accretion disks — binaries: eclipsing — stars: individual (MXB 1659-29) — stars: neutron — X-rays: stars

1. INTRODUCTION

During outburst episodes, neutron star X-ray transients can be detected at luminosities of \(\sim 10^{36–38}\) erg s\(^{-1}\) (Chen, Shrader, & Livio 1997). During those outbursts, the transients are very similar to the persistent sources with respect to their X-ray properties. The high X-ray luminosity is very likely due to the accretion of matter onto the neutron star. These transients are characterized by their bright outbursts, but most of the time, they are in a quiescent state in which they are orders of magnitude dimmer at all wavelengths. Fortunately, using sensitive imaging instruments, we are still able to detect them at X-ray luminosities of \(\sim 10^{32–34}\) erg s\(^{-1}\) (van Paradijs et al. 1987; Asai et al. 1996, 1998). The high-sensitivity cameras on board Chandra and XMM-Newton are well suited to detect quiescent systems and obtain good X-ray spectra for the brightest systems (Daigne et al. 2002; in ’t Zand et al. 2001; Rutledge et al. 2001a, 2001b; Wijnands et al. 2001b, 2002b). To explain the low quiescent X-ray properties, several models have been developed. For example, the X-rays could be due to the residual accretion of matter onto the neutron star or magnetospheric boundary, or the pulsar emission mechanism might be active (Stella et al. 1994; Corbet 1996; Campana et al. 1998b; Menou et al. 1999; Campaan & Stella 2000; Menou & McClintock 2001). Currently, the most successful model is that in which the X-rays are due to the thermal emission from the neutron star surface, which will be referred to as the cooling neutron star model.

1.1. The Cooling Neutron Star Model

In the cooling neutron star model (van Paradijs et al. 1987; Campana et al. 1998b; Brown, Bildsten, & Rutledge 1998 and references therein), the emitted radiation below a few keV is thermal emission originating from the neutron star surface. Brown et al. (1998) argued that the neutron star core is heated by the nuclear reactions occurring deep in the crust when the star is accreting, and this heat is released as thermal emission during quiescence. If the quiescent emission is dominated by the thermal emission of the cooling neutron star, then the quiescent luminosity should depend on the time-averaged (over \(10^{4–10^5} \text{ yr}\)) accretion luminosity of the system (Campana et al. 1998b; Brown et al. 1998). Thus, the quiescent luminosities of the detected systems can be compared directly with the predicted ones obtained from estimates of the long-term accretion history of the sources.

The neutron star cooling model also gives clear predictions for the spectral shape of the quiescent X-ray spectrum, which should be thermal. Although a simple blackbody model can be fitted to the data, the obtained radii of the emitting regions (of the order of only a few kilometers) are considerably lower than the predicted radii of neutron stars (Shapiro & Teukolsky 1983). To circumvent this discrepancy, it has been proposed that quiescent neutron star systems do not emit a true blackbody spectrum but a modified one (Brown et al. 1998). When using blackbody models to fit such modified spectra, the effective temperatures will be overestimated and the emitting areas underestimated. By fitting more realistic models, such as the so-called neutron star atmosphere models (the nonmagnetic models are appropriate for quiescent neutron star systems; Zavlin, Pavlov, &
Shibanov 1996) to the X-ray data, emitting radii were obtained that are consistent with the expected radii of neutron stars (Rutledge et al. 1999, 2000).

The cooling neutron star model cannot fully explain all characteristics of the quiescent emission. For example, the power-law shaped spectral component that dominates the quiescent spectra above a few keV in several systems7 (Asai et al. 1996, 1998; Campana et al. 1998a) cannot be explained by the cooling models. It is conceivable that this component might be described by one or more of the alternative models discussed above (in particular, the residual accretion model). However, the observational results on this component and our understanding of its nature are very limited.

1.2. The Quasi-persistent X-Ray Transients

Recently, a subgroup of neutron star X-ray transients has received extra attention because of their potential to test the cooling neutron star model and to determine some of the physical properties of the neutron star crust and core. These particular transients do not have traditional outbursts that only last weeks to at most a few months, but instead they stay active for several years to over a decade (and maybe even longer). These systems have been called long-duration transients or quasi-persistent sources (Wijnands et al. 2001b; Wijnands 2002). The long outburst behavior of those sources might be related to the extended episodes (several months to several years) of low-level activity seen in other transients usually after they have exhibited bright outbursts (e.g., in 4U 1630–47, Aql X-1, 4U 1608–52, or SAX J1808.4–3658; Kuulkers et al. 1997; Bradt et al. 2000; Wijnands et al. 2001c; Wachter et al. 2002), although those episodes are generally less luminous (<10^{36} ergs s^{-1}) than the outbursts of the quasi-persistent sources (10^{36}–10^{37} ergs s^{-1}).

In ordinary (i.e., short-duration) transients, the accretion of matter will have only a very minor effect on the thermal state of the crust, but for these quasi-persistent sources, the prolonged accretion episodes can heat the crust to high temperatures, considerably higher than that of the neutron star core (see Rutledge et al. 2002). When those systems become quiescent again, it might take years to decades for the crust to return to thermal equilibrium with the core, and the initial quiescent properties of those systems might be dominated by the crust emission and not by the state of the core (as is the case in ordinary transients). Monitoring observations of those systems in quiescence might even allow one to follow the cooling of the crust from which the heat conductivity of the crust can be determined (Rutledge et al. 2002).

Recently, one of the quasi-persistent systems (KS 1731–260) suddenly turned off after having actively accreted for over 12.5 yr. A Chandra observation taken a few months after this transition showed the source at a 0.5–10 keV luminosity of ∼10^{35} ergs s^{-1} (Wijnands et al. 2001b). An XMM-Newton observation of this system performed about half a year after the Chandra observation showed that the system had declined by a factor of ∼3 in luminosity (Wijnands et al. 2002b). If the quiescent emission from this system was dominated by the state of the crust, the decrease in luminosity within half a year strongly indicates that the crust must have a high heat conductivity (Wijnands et al. 2002b, using the cooling curves calculated for this system by Rutledge et al. 2002). In this scenario, the core temperature is expected to be lower than the crust temperature, and the luminosity measured with XMM-Newton can be used as an upper limit on the core luminosity. The quiescent luminosity of KS 1731–260 is much lower than expected from its long-term accretion history and can be explained only in terms of the standard cooling model if this system is dormant for at least several thousand of years between outbursts (assuming all outbursts of this system are very similar to the last one, which might not be a valid assumption—Wijnands et al. 2001b; Rutledge et al. 2002). Alternatively, enhanced cooling processes might be active in the core, rapidly cooling it (Wijnands et al. 2001b, 2002b).

1.3. MXB 1659–29

In 2001 September, the opportunity arose to use another quasi-persistent system to test the cooling neutron star model: MXB 1659–29. This source is an X-ray transient and was discovered in 1976 by Lewin, Hoffman, & Doty (1976) during type I X-ray bursts, which clearly demonstrates that the compact object in this system is a neutron star. The source was detected several times between 1976 October and 1978 September with S.A.S 3 and HEAO (Lewin et al. 1978; Share et al. 1978; Griffiths et al. 1978; Cominsky, Osman, & Lewin 1983; Cominsky & Wood 1984, 1989) and irregular X-ray variability was found in this system (Lewin 1979; Cominsky et al. 1983). Cominsky & Wood (1984, 1989) reported on the discovery of eclipses every ∼7.1 hr, which can be identified with the orbital period of the system. MXB 1659–29 is one of only several nonpulsating neutron star low-mass X-ray binaries for which total eclipses have been observed. (The other confirmed eclipsing neutron star systems are EXO 0748-676, GR S 1747-312, and AX J1745.6-2901, although several other systems [e.g., 4U 2129+47] show partial eclipses; Parmar et al. 1986; ’t Zand et al. 2000; Maeda et al. 1996; McClintock et al. 1982). During later observations using a variety of satellites (Hakucho, EXOSAT, and ROSAT), the source could not be detected any more (Cominsky et al. 1983; Verbunt 2001). The pointed ROSAT observations in the early 1990s failed to detect the source with a 0.5–10 keV upper limit on the unabsorbed flux of (1–2) × 10^{-14} ergs cm^{-2} s^{-1} (Verbunt 2001; Wijnands 2002; Oosterbroek et al. 2001).

The source remained dormant until 1999 April, when in ’t Zand et al. (1999) reported it to be active again in observations obtained with the BeppoSAX Wide Field Camera. Wachter, Smale, & Bailyn (2000) and Oosterbroek et al. (2001) obtained an updated ephemeris for the orbital period (using data obtained with the Rossi X-Ray Timing Explorer [RXTE] and BeppoSAX). Studies of its X-ray spectra were performed using BeppoSAX (Oosterbroek et al. 2001) and XMM-Newton (Sidoli et al. 2001), and using RXTE data, Wijnands, Strohmayer, & Franco (2001a) found ∼567 Hz oscillations during X-ray bursts. Those oscillations are likely related to the neutron star spin frequency. The source remained bright for almost 2.5 yr before it became dormant again in 2001 September (Wijnands et al. 2002a). Because of its long outburst duration, MXB 1659–29 may be classified as a quasi-persistent source. We had a Cycle 3 Chandra Target of Opportunity proposal approved to obtain a quiescent observation of the next quasi-persistent source that

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7 Note that not in all detected quiescent systems this power-law component could be detected and that the flux ratio of the power-law component with the thermal component varies considerably between sources.
could turn off, within a month after the transition. As part of this proposal, MXB 1659–29 was observed on 2001 October 15 using Chandra for \( \sim 19 \) ks. Here we report on this observation.

2. OBSERVATION, ANALYSIS, AND RESULTS

The RXTE All-Sky Monitor (ASM) light curve of MXB 1659–29 is shown in Figure 1 (see also Wijnands et al. 2002a). As can clearly be seen, MXB 1659–29 stayed active during its last outburst for almost 2.5 yr before it could not be detected any more with the RXTE/ASM at the end of 2001 August. During more sensitive observations using the proportional counter array (PCA) on board RXTE, the source could still be detected until 2001 September 7, but it was undetectable in observations performed on 2001 September 14, 24, and 30 (Wijnands et al. 2002a; with upper limits on the flux of 0.5–1 mcrab: 2–60 keV).

After the nondetection using the RXTE/PCA on 2001 September 14, we triggered our Cycle 3 Chandra proposal and a Chandra/ACIS-S observation on MXB 1659–29 was performed on 2001 October 15 between 16:31 and 22:24 UTC for a total of \( \sim 18.8 \) ks of on-source time. No background flares occurred during the observation, so all data could be used. We used the CIAO tools (v. 2.2.1) and the standard Chandra analysis threads\(^8\) to analyze the data. During our observation, the ACIS-S3 CCD was used with a 1/4 subarray (resulting in a frame time of 0.8 s). This configuration was used to reduce the possible pile-up problems in case the source had exceeded a flux level of \( \sim 10^{-12} \) ergs cm\(^{-2}\) s\(^{-1}\). As demonstrated below, only about 2\% pileup occurred during our observation because of the relatively low flux of the source.

\(^8\) Listed at http://asc.harvard.edu.

2.1. X-Ray Image and Light Curve of MXB 1659–29

The obtained 0.5–8 keV image of the region around MXB 1659–29 is shown in Figure 2. We used the tool wavdetect to search the complete chip for point sources. The three sources visible in Figure 2 are detected (their coordinates are listed in Table 1) together with two additional, rather diffuse sources, which could be truly diffuse sources or due to an elevated background count rate at those positions. In this paper, we are interested only in the properties of MXB 1659–29, so we do not further investigate the significance of those potential sources. We used the optical I-band images of Wachter et al. (2000) taken during outburst to determine possible optical counterparts for the detected Chandra sources. We tied these optical images to the Two-Micron All-Sky Survey (2MASS) \( J \) image available for this region; the resulting image, including the Chandra positional circles, is shown in Figure 3. Clearly, the Chandra position of MXB 1659–29 is consistent with its optical position during outburst, with an offset of only \( \sim 0.15 \) arcsec, well within the bore sight error (Aldcroft et al. 2000) and the errors on the optical position. The positions listed in Table 1 are adjusted for this small offset. The two extra Chandra sources do not have counterparts in the optical image.

### TABLE 1

| Name          | R. A.        | Decl.        |
|---------------|--------------|--------------|
| MXB 1659–29   | 17 02 06.54 ± 0.02 | −29 56 44.1 ± 0.3 |
| CXOU J170207.1–295535 | 17 02 07.06 ± 0.02 | −29 55 34.7 ± 0.3 |
| CXOU J170205.9–295619  | 17 02 05.93 ± 0.02 | −29 56 19.2 ± 0.4 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
Figure 4 displays the Chandra/ACIS-S light curve. It clearly shows an eclipse, which is very likely due to the obscuration of the inner X-ray–emitting region by the companion star (cycle 30823 using the linear ephemeris of Oosterbroek et al. 2001). The eclipse duration (842 s) and the egress and ingress times (<247 and <400 s, respectively) have been calculated using the method outlined by Nowak, Heinz, & Begelman (2002). The obtained eclipse duration is consistent with that observed during outburst (~900 s; Wachter et al. 2000). Eclipses in quiescence have also been observed for the neutron star transient 4U 2129+47 (Nowak et al. 2002) and from the likely neutron star transient X5 in the globular cluster 47 Tuc (Heinke et al. 2001, 2002). Besides the eclipse, the Chandra/ACIS-S light curve also shows clear dipping behavior a few kiloseconds before the eclipse, which again is very similar to 4U 2129+47 and X5 in 47 Tuc. Those dips might be due to the same process causing the dipping behavior of the source when it is still actively accreting: the dips might be due to obscuration of the central X-ray source by a large structure in the outer accretion disk, possibly the impact point of the accretion stream from the companion star and the accretion disk. (See also Nowak et al. 2002 and Heinke et al. 2001, 2002 for a discussion of the dips for 4U 2129+47 and X5, respectively.) The decrease in count rate would then be due to an increase in the absorption column in front of the central X-ray source. This hypothesis can be tested by examining the spectrum of the source in and outside the dip (see § 2.3). Note that this hypothesis requires that residual disks are still present in quiescence without accretion occurring onto the neutron stars. Indeed, such residual disks are expected from the disk instability model to explain X-ray outbursts (see Lasota 2001 for a review), and independent proof for such disks came from optical observations from quiescent X-ray transients (McCintock & Remillard 2000).

2.2. The X-Ray Spectrum of the Persistent Emission

All X-ray spectra were extracted using a circle with 5″ radius on the position of the source as determined using wavdetect, and the background data were obtained by using an annulus on the source position with an inner radius of 7″ and an outer one of 20″. All obtained spectra were rebinned using the FTOOLS tool grppha into bins with a minimum of 15 counts per bin, and we fitted the spectrum using XSPEC (version 11.1; Arnaud 1996). We extracted spectra for the part of the observation during which the source was relatively stable (called the persistent spectrum; see Fig. 4; ~13.2 ks of data) and for the part during the dips (called the dip spectrum; Fig. 4; a total of ~3.8 ks of data).

Many single-component models fit the persistent spectrum well; however, the quiescent spectra of neutron star X-ray transients are most often fit with a blackbody model or a neutron star atmosphere model. Therefore, we concentrate on those two models, using the model from Zavlin et al. (1996; the nonmagnetic case) as the atmosphere model. Theoretically, it is expected that the emerging spectrum should resemble that assumed by the atmosphere model (Brown et al. 1998); however, observationally, both the atmosphere model and the blackbody model produce equally satisfactory fits to the data. Because our data do not allow for a rejection of the blackbody model and to allow comparison with previous results the quiescent spectra of neutron star X-ray transients, we also report the blackbody results. In certain systems, a power-law tail above a few keV was found, and although such a power-law component was not required by the data, we fitted the spectra with the above two models, including a power-law component with a photon index of 1 or 2 to obtain an upper limit on this component.
TABLE 2

| Parameter                        | Persistent | Persistent + Dip |
|----------------------------------|------------|-----------------|
| $N_H^{\text{persistent}}$ (10^{22} cm^{-2}) | 0.22$^{+0.07}_{-0.06}$ | 0.19$^{+0.07}_{-0.06}$ |
| $N_H^{\text{diff}}$ (10^{22} cm^{-2}) | ... | 0.35$^{+0.13}_{-0.08}$ |
| $kT$ (keV)                       | 0.28$^{+0.02}_{-0.03}$ | 0.28$^{+0.02}_{-0.03}$ |
| Radius (d/10 kpc km)             | 2.4$^{+1.5}_{-0.8}$ | 2.1$^{+1.8}_{-0.7}$ |
| $F_{\text{persistent}}$          | 3.0        | 2.7             |
| $\chi^2$/dof                     | 32.2/37    | 45.2/43         |

Note.—Error bars represent 90% confidence levels. The fluxes are unabsorbed, in the 0.5–10 keV range, and in units of 10^{-13} ergs cm^{-2} s^{-1}. As a blackbody model, we used the bbodyrad model in XSPEC. For the hydrogen atmosphere model, we used the model of Zavlin et al. 1996 (the nonmagnetic case) and for this model the neutron star mass was fixed to 1.4 $M_\odot$ and the temperature and radius are for an observer at infinity. For both models, the distance $d$ was assumed to be 10 kpc.

The spectral results are listed in Table 2, and the persistent spectrum is shown in Figure 5. The column density $N_H$ was left free in the fits, and the obtained value is in the range of what has been observed previously for this source during outburst using BeppoSAX and XMM-Newton ([0.13–0.35] × 10^{22} cm^{-2}; Oosterbroek et al. 2001; Sidoli et al. 2001). Both the blackbody and the atmosphere model fit the data well, and the best-fit temperature was $\sim$0.3 keV for the blackbody fits and $\sim$0.1 keV for the atmosphere model.\(^9\) When assuming a distance of 10 kpc,\(^10\) the radius for the emitting area was only a few kilometers using the blackbody model, which is lower than the theoretical expected radius for a neutron star. The atmosphere model gave radii that were consistent with those expected if the emission arose from the neutron star and the complete surface was radiating, favoring the atmosphere model. For larger assumed distances the radii would increase, although the distance has to be unrealistically large ($>20$ kpc) for the radius obtained via the blackbody model to become consistent with theoretical expectations. The atmosphere model does not allow for the distance to become much larger than assumed because the obtained radius will quickly be inconsistent with theoretical expectations.

The obtained unabsorbed 0.5–10 keV fluxes were between 3.0 and 3.6 $\times 10^{-13}$ ergs cm^{-2} s^{-1}, resulting in a luminosity of (3.6–4.3) $\times 10^{33}$ (d/10 kpc)$^2$ ergs s^{-1}. When including a power-law component in the fit, it could not be detected significantly, and its 0.5–10 keV flux could be constrained to be less than about 25%–35% (depending on photon index) of the 0.5–10 keV blackbody flux or that of the atmosphere component.

2.3. The Spectrum during the Dip

Due to the low statistics of the dip data, the source spectrum during the dip could not be constrained by using only the dip data. However, by assuming that the decrease in count rate is only due to an increase in absorption by obscuring material (as has been found during outburst; Oosterbroek et al. 2001; Sidoli et al. 2001), we fitted the persistent spectrum and the dip spectrum simultaneously, using the same blackbody or atmosphere model but with different

\(^9\) Using the obtained spectral parameters in this paragraph and the 0.8 frame time of our observation, we have used PIMMS to estimate the degree of pileup in our spectrum. We found that about 2% of the photons should be piled up, and the effects on the X-ray spectral parameters were only marginal. Therefore, we have not corrected the X-ray spectrum for this effect.

\(^10\) The distance toward the source is not well known. Using the luminosity of the X-ray bursts detected during the 1999–2001 outburst, Oosterbroek et al. (2001) obtained a range of 11–13 kpc but Muno et al. (2001) reported 10 kpc. In the remaining, we will assume 10 kpc, but we note that it is rather uncertain. When appropriate, we will discuss the effect of this uncertainty on the interpretation of our results.

![Figure 5](https://example.com/figure5.png)

**Fig. 5.—** Chandra/ACIS-S spectrum of MXB 1659−29 of the persistent part of the data. **Top panel, solid line:** Best blackbody fit to the data. **Bottom panel:** Best neutron star atmosphere model fit.
column densities. The spectral results are also listed in Table 2. The spectral parameters of the persistent emission were consistent with those obtained when only fitting the persistent emission spectrum, although the measured fluxes tend to be slightly lower. The column density of the dip spectrum is higher (by a factor of 2) than that obtained for the persistent emission. Figure 6 shows the error ellipse of the column density of the persistent emission spectrum versus that of the dip spectrum. Clearly, at high significance, it is rejected that the column density of the dip spectrum is identical to that of the persistent emission. A systematic trend is clearly seen that the dip column density is always larger than that of the persistent emission. (A similar result is obtained when the atmosphere model is used instead of the blackbody model.) Our results show that our data are consistent with a scenario in which the intrinsic source spectrum remains identical throughout the Chandra observation, and that the decrease in count rate during the dip is due to an increase in absorption, but we cannot exclude other mechanisms responsible for the count rate decrease. For example, the data are also consistent with a decrease in luminosity without a change in spectral shape or with a decrease of the temperature.

The observation of a dip in the quiescent X-ray light curve of MXB 1659–29 might imply that absorption by the outer disk also could occur, albeit less strong, during the orbital phases where no dips are observed, possibly affecting the spectral fits of the persistent emission. However, during the outburst phase of the source, type I X-ray bursts were observed and nearly coherent oscillations were seen during those bursts (Wijnands et al. 2001a), implying that the neutron star is observed directly. Very likely, this will also be true during quiescence. Furthermore, the measured column density toward the source from the persistent quiescent emission is rather low and consistent with other estimates and measurements (Dickey & Lockman 1990; Oosterbroek et al. 2001; Sidoli et al. 2001), making additional absorption by the outer disk also unlikely. Therefore, we conclude that very likely we see the neutron star directly at orbital phases outside the dip and the eclipse, and our spectral results can be compared directly with the results obtained from other quiescent neutron star transients that have lower binary inclination than MXB 1659–29.

3. DISCUSSION

We have presented a Chandra observation of MXB 1659–29 performed ~5 weeks after the last clear detection of the source with the RXTE/PCA (indicating that at that time the source was still actively accreting; Wijnands et al. 2002a). During our Chandra observation, we detected the source at a luminosity of (3.2–4.3) × 10^{33} (d/10 kpc)^2 ergs s^{-1}, and its spectrum could be well described by a thermal component (either a blackbody model or a neutron star atmosphere model). The obtained luminosity and the shape of the X-ray spectrum of MXB 1659–29 resemble those obtained for other quiescent neutron star systems, strongly suggesting that the source was quiescent during our Chandra observation.

3.1. The Cooling Neutron Star Model

As argued by Rutledge et al. (2002), for systems that are actively accreting for long periods, the crust might have been heated to very high temperatures (probably considerably higher than that of the core), and the quiescent properties might be dominated by the thermal state of the crust rather than that of the core. Although the duration of the accretion episode of MXB 1659–29 is considerably shorter (by a factor of ~5) than that of KS 1731–260 or X 1732–304 (both of which had accretion episodes of more than a decade; Wijnands et al. 2001b, 2002b; see also Guainazzi, Parmar, & Oosterbroek 1999 for X 1732–304), here we assume that the 2.5 yr accretion episode of MXB 1659–29 has had a considerable effect on the state of the crust, similar to what has been argued for KS 1731–260 (Rutledge et al. 2002; although likely less extreme).

This assumption is also supported by the fact that in the early 1990s, the source could not be detected in quiescence using a ROSAT observation and only a 0.5–10 keV upper limit of (1–2) × 10^{32} (d/10 kpc)^2 ergs s^{-1} could be obtained (Verbunt 2001; Wijnands 2002; Oosterbroek et al. 2001), which is about an order of magnitude lower than the luminosity we have detected during our Chandra observation. Therefore, we can conclude that the Chandra quiescent luminosity is not the rock bottom quiescent luminosity of this system, and the quiescent properties for MXB 1659–29 during the Chandra observation were dominated by that of the crust and not by the core. As an upper limit on the flux due to the cooling neutron star core, we will assume the upper limit provided by ROSAT, and this upper limit will be used to test the cooling neutron star model.

In order to test the model, the time-averaged accretion rate has to be estimated. The last outburst was fully covered with the RXTE/ASM instrument (Fig. 1) and lasted for ~2.5 yr. The 2–10 keV luminosity during this state as obtained with BeppoSAX and XMM-Newton was about 6 × 10^{30} ergs cm^{-2} s^{-1} (Oosterbroek et al. 2001; Sidoli et al. 2001). Using the spectral model and the spectral parameters given by Oosterbroek et al. (2001), we inferred (by simulating the spectrum in XSPEC) that the bolometric luminosity can be at least a factor of 2 larger. However, the luminosity itself was variable (by a factor of a few; Fig. 1) during the outburst, and large uncertainties might be
present in the typical outburst bolometric luminosity. How-
however, in the rest of the discussion, we assume that bolometric
outburst flux was typically \((5-10) \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1}\)
during the last outburst.

The 1999–2001 outburst could be an atypical one for MXB 1659–29, and previous outbursts might have been less bright and/or less long (i.e., more like those of the ordinary transients). We have searched the literature for reports on detections of this source in the past, and we found that the source was conclusively detected in X-rays in 1976 October, 1977 June, July, \(^{11}\) and September, and 1978 March and September using SAS 3 and HEAO (Lewin et al. 1976, 1978; Share et al. 1978; Griffiths et al. 1978; Lewin 1979: Cominsky et al. 1983; Cominsky & Wood 1984, 1989) and in the optical on 1978 June 1 and 1979 June 27–July 2 (Doxsey et al. 1979; Cominsky et al. 1983). No information is available during the periods in between those observations. Although it cannot be excluded that at those occasions the source was in quiescence, we consider it unlikely that the source would be active only during times when it was observed with an X-ray or optical instrument and dormant when no instrument looked at it. Therefore, it is likely that during the complete period from 1976 October until early 1979 July, the source was actively accreting for over 2.5 yr, especially because the recent outburst had a similar duration. If true, then this would constitute the first indication that different outbursts of quasi-persistent sources may have similar durations and that the long duration of those outbursts might be a common property of those sources.

The first reported nondetection of the source was on 1979 July 17–25 (Cominsky et al. 1983) in optical \((V > 22-23)\) and with Hakuchou (no X-ray upper limits were provided). Prior to 1976, the source might have also been detected during the period 1971 to 1973 using Uhuru (classified as 4U 1704–30; Forman et al. 1978), although this identification with MXB 1659–29 is not certain, and we will assume that they are two different objects. (If 4U 1704–30 can be identified with MXB 1659–29, then the source might have exhibited an extra outburst during that period, or it might have been active for a period of \(\sim 7 \text{ yr}\).) The exact fluxes during the observations in the period 1976 October to 1979 early July are in the range \((1-6) \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1}\), but they have large uncertainties because the exact energy range was not always quoted (if quoted, it was \(1-10 \text{ or } 2-10 \text{ keV}\)), it was unclear if the fluxes were absorbed or unabsorbed, and the assumed spectral shape was not always similar (often assumed to be Crab-like) and quite different than observed with BeppoSAX and XMM-Newton during the 1999–2001 outburst (Oosterbroek et al. 2001; Sidoli et al. 2001). However, we will assume that all fluxes are for the \(2-10 \text{ keV}\) range and unabsorbed and a bolometric flux of about twice the quoted values (as inferred above for the BeppoSAX results on MXB 1659–29). Therefore, during the outburst in the late 1970s, the source was actively accreting for a period of at least \(\sim 2.5 \text{ yr}\) at a bolometric flux level of \((2-12) \times 10^{10} \text{ ergs cm}^{-2} \text{ s}^{-1}\). Although quite uncertain, this is remarkably similar to the values of the 1999–2001 outburst and, for simplicity, we assume that the typical outburst duration is \(2.5 \text{ yr}\) and that the bolometric fluxes during outburst is \((5-10) \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1}\).

Using the Brown et al. (1998) model (assuming standard cooling processes), the predicted quiescent flux \(F_q\) for this source would then be \((\text{Wijnands et al. 2001b; see also Rutledge et al. 2002}) F_q \approx t_q/(t_q + t_o) \times (F_o)/135, \) with \(\langle F_o \rangle\) the average flux during outburst \(\{(5-10) \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1}\}\), \(t_o\) the average time the source is in outburst \((2.5 \text{ yr})\), and \(t_q\) the average time the source is in quiescence \((\sim 21 \text{ yr})\). This results in a predicted quiescent flux of \((4-8) \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}\). Remarkably, this value is very similar to the quiescent flux observed during our Chandra observations. However, as explained above, on the basis of the ROSAT nondetection of the source, the core flux is likely at least an order of magnitude lower than this, which would make the predicted core flux considerably higher than that truly originating from the core. Similar to KS 1731–260 (Wijnands et al. 2001b, 2002b), this low core flux (and, thus, temperature) might be due to enhanced core cooling instead of the assumed standard core cooling in the Brown et al. (1998) model.

Despite the fact that the last two outburst episodes are likely of similar duration, it cannot be excluded that they are not typical for the source and that most of the time MXB 1659–29 exhibits short-duration outbursts. If the typical outburst duration of MXB 1659–29 is not \(2.5 \text{ yr}\) but instead \(0.25 \text{ yr (3 months)}\) or shorter, then the predicted quiescent flux will be consistent (within the uncertainties of the model and assumptions) with the ROSAT upper limit. The higher \(\text{Chandra}\) quiescent luminosity is again due to the state of the crust, which should be considerably heated during the long accretion episode.

### 3.2. Crust Cooling

If during the \(\text{Chandra}\) observation the X-ray emission was dominated by thermal emission from the crust, then further quiescent observations of MXB 1659–29 will enable studies of the cooling of the crust in this system. The \(\text{ROSAT}\) flux upper limit suggests that the crust flux should eventually decrease to at least this level. When the crust will be thermally relaxed with the core, no significant further decrease of the quiescent flux is expected, and from this bottom flux level, the state of the core can be inferred from which the cooling models can be better constrained. For KS 1731–260, it had already been found that its quiescent luminosity decreased by a factor of 3 within half a year’s time (likely due to a temperature decrease), indicating a highly conductive crust (Wijnands et al. 2002b). It would be of interest to determine if such a rapid cooling will also be observed for MXB 1659–29 or if the neutron star crust in this system has a significantly lower conductivity.

In the latter case, the system should be at the \(\text{Chandra}\) quiescent luminosity for several years to decades. Using the fact that 13 yr after the 1976–1978 outburst, \(\text{ROSAT}\) observed an order of magnitude lower quiescent luminosity, we might have already set an upper limit on the crust cooling time. When assuming that shortly after the end of the 1976–1978 outburst the quiescent luminosity was similar to our measured \(\text{Chandra}\) luminosity, the cooling time of the crust is at least about a factor of 10 in luminosity per decade. Due to differences in quiescent times, outburst times, and the time-averaged accretion rates between MXB 1659–29 and KS 1731–260, the cooling curves calculated for

\(^{11}\) During 1977 June and July, the observations were not very sensitive to persistent X-ray emission and none was detected (Cominsky & Wood 1984, 1989). But X-ray bursts were observed from the source, indicating that also during those observations, the source was accreting, albeit at a low level.
KS 1731–260 by Rutledge et al. (2002) cannot be used for MXB 1659–29. However, if those MXB 1659–29 cooling curves resemble those of KS 1731–260, then tentatively, it also might be concluded that the neutron star crust in MXB 1659–29 has a high conductivity (and enhanced core cooling is suggested). We await specifically calculated cooling curves for MXB 1659–29 and further monitoring observations using Chandra or XMM-Newton in order to be conclusive about the properties of the neutron star in this system.

3.3. Very Low Thermal Emission in Quiescent Neutron Star Systems?

For most quiescent neutron star X-ray transients, it has been inferred that the thermal emission is in the range of a few times 10^{32}–10^{33} ergs s^{-1}. However, recently, indications have been found (using XMM-Newton data) that the thermal emission from the accretion-driven millisecond X-ray pulsar SAX J1808.4–3658 in its quiescent state might be as low as a few times 10^{30} ergs s^{-1} (Campana et al. 2002, who suggested enhanced core cooling for this low thermal luminosity). Although the statistics of those results were not overwhelming and have to be confirmed with additional observations, it is an interesting possibility, and if the processes that produced the quiescent emission (which has a power-law shape; Campana et al. 2002) for this system would become inactive, SAX J1808.4–3658 would become rather dim in quiescence. Such weak quiescent neutron star systems might also be suggested by the indications found for enhanced cooling processes in certain systems, such as MXB 1659–29. The possibility of dim quiescent neutron star systems raises the question of how dim certain neutron star systems can become.

The answers to this question will have implications for our understanding of quiescent X-ray binaries. It has been found that those X-ray binaries that harbor a black hole instead of a neutron star can be at least 1–2 orders of magnitude less luminous in quiescence than the average neutron star system. This difference has been used as evidence that the black holes have event horizons (García et al. 2001 and references therein) in contrast to the surfaces of neutron stars. However, if certain neutron star systems might become similarly dim (e.g., due to enhanced core cooling or very dim outbursts), then this luminosity difference will disappear and, with it, the evidence for event horizons in black hole systems. The quiescent spectrum of SAX J1808.4–3658 (Campana et al. 2002) indicates that the spectrum of such systems might not be dominated by a thermal component but might have a power-law shape similar to what has been seen for the black hole systems (Kong et al. 2002), removing also the spectral differences.

Another area in which it might be important to determine the full range of the luminosity distribution of quiescent neutron star systems is that of the study of the low-luminosity X-ray sources in globular clusters. On the basis of their luminosities and their X-ray spectra (when enough statistics are available), those sources that have luminosities above a few times 10^{32} ergs s^{-1} have been classified as quiescent neutron star systems, and those that have luminosities below 10^{32} ergs s^{-1} as another type of object (possible cataclysmic variables or millisecond radio pulsars). However, the observed low luminosity of 5 \times 10^{31} ergs s^{-1} of SAX J1808.4–3658 (Dotani, Asai, & Wijnands 2000; Campana et al. 2002) already shows (irrespective of what exactly causes the X-rays in this source) that those dim sources might be quiescent neutron star transients. The fact that the spectrum of SAX J1808.4–3658 appears to be considerably harder (Campana et al. 2002) than the average quiescent neutron star spectrum indicates that classifications on hardness ratio might lead to erroneous results. The possibility that the thermal emission of SAX J1808.4–3658 might be very low even suggests that those sources that have luminosities down to only a few times 10^{30} ergs s^{-1} might also be quiescent neutron star systems. Therefore, we conclude that classifying low-luminosity globular cluster sources on the basis of their luminosity and broadband spectral shape (i.e., hardness ratios) might possibly produce misleading results. The full extent of those errors depends on the full luminosity distribution of the quiescent neutron star transients and how the spectrum correlates with the luminosity. Those properties have to be determined before a complete picture of the nature of the low-luminosity globular cluster sources can be understood.\(^\text{12}\)

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\(^\text{12}\) Although we have only discussed quiescent neutron star systems, similar uncertainties in the luminosity distribution of CVs or millisecond radio pulsars exist. Those uncertainties in the properties of those systems have to be resolved before a full understanding of the low-luminosity globular cluster source population can be obtained.

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