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THE CRUST COOLING CURVE OF THE NEUTRON STAR IN MXB 1659–29

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RESUMEN

Hemos monitoreado con Chandra MXB 1659-29, un sistema transitorio en rayos X, en su etapa de quietud. El propósito de nuestras observaciones es documentar el comportamiento de este objeto en su etapa de quietud, después de su último y extenso episodio explosivo y estudiar la curva de enfriamiento de la estrella de neutrones de este sistema. En este artículo discutimos nuestros resultados, así como las implicaciones que éstos tienen en la restricción de las propiedades de la estrella de neutrones del sistema MXB 1659-29.

ABSTRACT

We have monitored the quasi-persistent neutron-star X-ray transient MXB 1659–29 in quiescence using *Chandra*. The purpose of our observations was to monitor the quiescent behavior of the source after its last prolonged outburst episode and to study the cooling curve of the neutron star in this system. We discuss the results obtained and how they constrain the properties of the neutron star in MXB 1659–29.

Key Words: **STARS: INDIVIDUAL (MXB 1659–29) — STARS: NEUTRON — X-RAYS: STARS**

1. INTRODUCTION

Neutron-star X-ray transients spend most of their time in a quiescent state during which hardly any or no accretion takes place. However, occasionally they can become very bright in X-rays due to a huge increase in the accretion rate onto their neutron stars. Most neutron-star transients are only active for several weeks to a few months at most, but several systems have been found to be active for years and even decades. Those systems have been called 'quasi-persistent' neutron-star X-ray transients.

During an outburst of the 'ordinary' transients, the neutron-star crust is only marginally heated. However, in the quasi-persistent transients the neutron star is significantly affected by the accreted material (e.g., Wijnands et al. 2001; Rutledge et al. 2002). In particular, the neutron-star crust is heated to high temperatures and will become considerably out of thermal equilibrium with the core (Rutledge et al. 2002). After the end of the outbursts, the crust will cool until it is again in thermal equilibrium with the core. The cooling time depends on the microphysics of the crust and the core, and the accretion history of the source (Rutledge et al. 2002).

Wijnands et al. (2001) observed the quasi-persistent transient KS 1731–260 with *Chandra* within a few months after its last outburst (which lasted for ∼12.5 years). Wijnands et al. (2002) reported on an *XMM-Newton* observation of the source taken ∼6 months after this *Chandra* observation and found that within half a year the source had decreased in 0.5–10 keV flux by a factor of ∼3. Rutledge et al. (2002) have calculated crust cooling curves for the neutron star in KS 1731–260 and based on those curves Wijnands et al. (2002) concluded that the neutron star in this system must have a large thermal conductivity in its crust and enhanced core cooling processes. In September 2001, a second quasi-persistent transient (MXB 1659–29) turned off. We initiated a monitoring campaign using *Chandra* to study the crust cooling curve of the neutron star in this system. Here we briefly describe the results of this campaign (for a detailed discussion see Wijnands et al. 2003, 2004).

2. OBSERVATIONS AND RESULTS

The quasi-persistent neutron-star X-ray transient MXB 1659–29 was active in the mid 1970's for ∼2.5 years after which it remained quiescent until April 1999 (in 't Zand et al. 1999; see Wijnands et al. 2003 for an overview of the accretion history of MXB 1659–29). Again the source remained active for ∼2.5 years until September 2001. Figure 1 shows the X-ray count-rate curve as obtained with the all-sky monitor (ASM) aboard the *Rossi X-ray Timing Explorer* (*RXTE*) showing this recent outburst (see also Wijnands et al. 2003). As explained above (§1) this 2.5 year outburst episode should have heated the neutron-star crust out of thermal equilibrium with the core and, once back in quiescence, the crust should slowly cool until it comes to thermal equilibrium again with the core. Therefore, we initiated a monitoring campaign with *Chandra* to study

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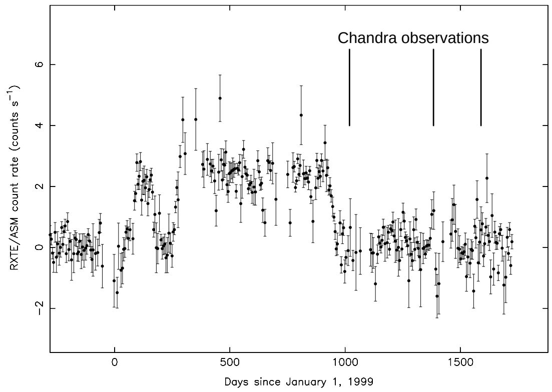

Fig. 1. The ASM count-rate curve of MXB 1659–29 showing the ∼2.5 year outburst. The times of the *Chandra* observations are indicated by the vertical lines

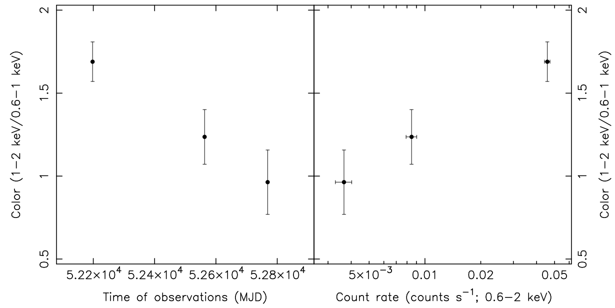

Fig. 2. The color vs. time (left) and color vs. the count rate (right) during those observations.

the cooling curve of this source. The details of those *Chandra* observations are given in Wijnands et al. (2003, 2004). The observations were taken ∼1, ∼12, and ∼19 months after the end of the prolonged outburst (see Fig. 1).

For each observation we obtained the background-corrected count rates and calculated a X-ray color (see Wijnands et al. 2004 for details about the extraction method and regions). We used the 0.6–2 keV count rate and the ratio of the 1–2 keV count rate to the 0.6–1 keV count rate as X-ray color. Those particular energy ranges were chosen because the source was detected during each observations in the energy range 0.6–2 keV (i.e., during the last observation hardly any source photons were found outside this range). The 0.6–2 keV count rate decreased significantly with time (by a factor of ∼10; Wijnands et al. 2004). In Figure 2 we show the behavior of the color with respect to time and with respect to the 0.6–2 keV count rate. As the source decreased in luminosity (i.e., as the quiescence time increased), its spectrum became softer. This softening cannot be explained by the decrease in time of the ACIS quantum efficiency (the colors are not corrected for this) since this degradation occurs mostly at soft energies. If the colors were corrected for this degradation they would become even lower in time.

If the observed X-rays are due to emission from the neutron-star surface, then the softening of the spectra with time would suggest that the temperature of the neutron-star crust decreased considerably in time. To test this hypothesis, we extracted the X-ray spectrum for each observation (see Wijnands et al. [2004] for details). The obtained spectra (corrected for background and ACIS efficiency degradation) are shown in Wijnands et al. (2004). The spectra were fitted with a neutron-star atmosphere (NSA) model for non-magnetized neutron stars (i.e., that of Zavlin et al. [1996] and Gänsicke et al. [2002]; assuming a canonical neutron star with a mass of 1.4 solar masses and a radius of 10 km; the distance toward the source was assumed to be 10 kpc). The decrease in count rate and the softening of the spectra with time can be explained by a decrease in bolometric flux due to a decrease in effective temperature. In Figure 3 we show the bolometric flux (top panels) and effective temperature (bottom panels) of the neutron-star crust as a function of time. The left panels were obtained by using the Zavlin et al. (1996) NSA model (see also Wijnands et al. 2004) and the right panels by using the Gänsicke et al. (2002) model (which could not be displayed by Wijnands et al. 2004 because of space limitations).

When using the Gänsicke et al. (2002) NSA model we get slightly higher temperatures (and consequently also higher bolometric luminosities) than when using the Zavlin et al. (1996) NSA model. This is a known discrepancy between the two models and the reason for this is not understood (Gänsicke et al. 2002). However, no significant differences are found in the way the bolometric flux and the effective temperature decrease with time: for both curves the decrease can be described as an exponential decay function with *e*-folding times of 262±33 and 282±19 days for the bolometric flux and 1060±126 and 1096±129 days for the effective temperature (for the Zavlin et al. [1996] and the Gänsicke et al. [2002] models respectively).

3. CONCLUSION

Our results show that in its quiescent state MXB 1659–298 significantly decreased in brightness within 1.5 years after the end of its last prolonged outburst. Along with this brightness decrease, the source became progressively softer, independently of which

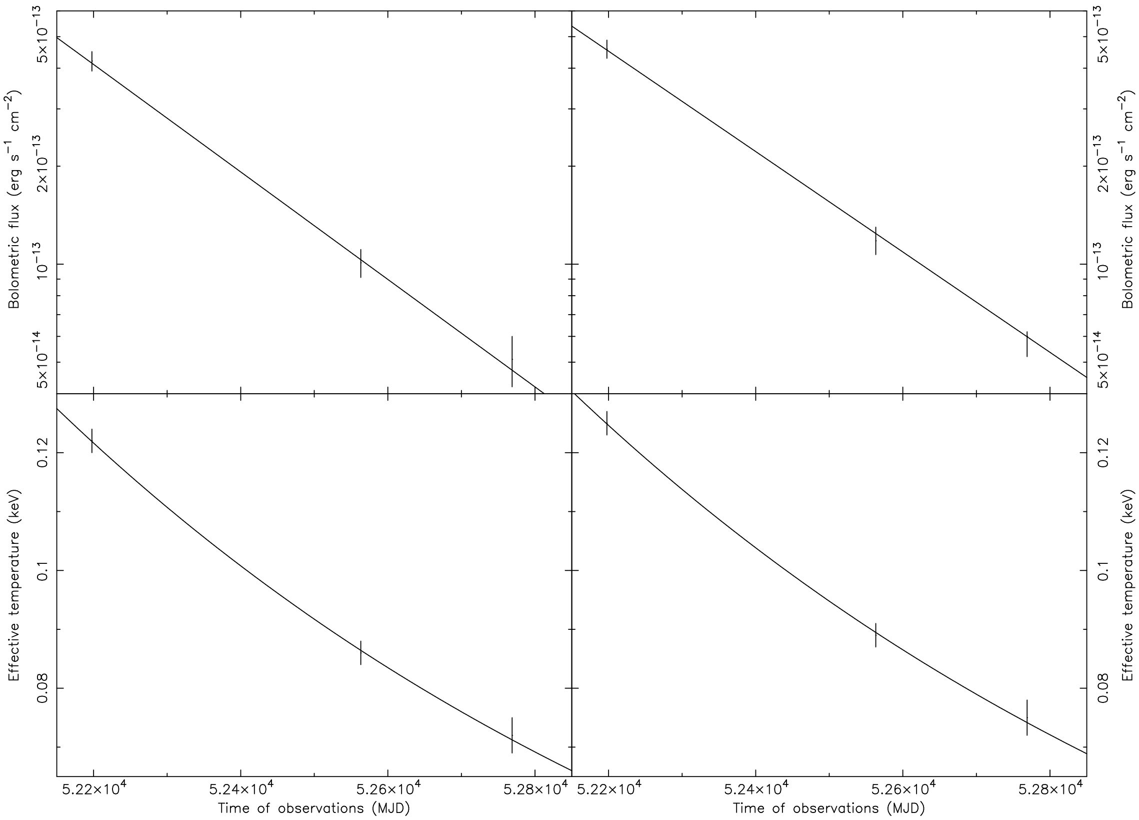

Fig. 3. The bolometric flux (top panels) and effective temperature curves (bottom panel; for an observer at infinity). The left panels are obtained by using the NSA model of Zavlin et al. (1996) and the right panels by using that of Gänsicke et al. (2002) (assuming a hydrogen atmosphere and for a non-magnetized neutron star).

model is fit to the spectral data. When the X-ray spectra obtained are fitted with a NSA model, this brightness decrease and softening of the spectrum can be explained as a decrease in effective temperature of the neutron-star surface. Wijnands et al. (2004) suggested that we see the neutron-star crust cool in time and that the fast cooling time might suggest that the neutron-star crust has a large thermal conductivity and that enhanced core cooling processes occur in the core. Detailed cooling curves specifically calculated for MXB 1659–29 (similar to those calculated for KS 1731–260 by Rutledge et al. 2002) are needed to determine whether these conclusions will hold and what the exact impact of our observations are for our understanding of the neutron-star properties in MXB 1659–29.

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