Rapid Cooling of the Neutron Star in the Quiescent Super-Eddington Transient XTE J1701−462

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1 Introduction

In the past decade the observing of cooling neutron star (NS) transients after long-duration outbursts has entered as a new approach to constraining the properties of matter inside neutron stars [1,2]. Heating due to transient accretion for extended periods (~year or longer) can significantly alter the temperature of a NS crust and bring it out of thermal equilibrium with the core. After accretion stops the crust is expected to cool down to equilibrium over several years. The timescale of the cooling depends on the properties of the matter in the crust, whereas the equilibrium temperature to which it cools is set by the temperature of the core, which in turn depends sensitively on the properties of the core matter.

2 XTE J1701−462

During its 19-month-long 2006-2007 outburst XTE J1701−462 became one of the most luminous NS low-mass X-ray binaries (NS-LMXBs) ever observed in the Galaxy, reaching a peak luminosity of ~1.5 L_{Edd} and accreting at near-Eddington luminosities throughout most of the outburst [3] (see Fig. 1). This source represents new parameter space being covered in NS cooling; it is set apart by the extraordinarily high level of its accretion and by the length of the outburst being intermediate between those of regular transients and those of the cooling quasi-persistent transients observed so far.

3 Transition to quiescence

XTE J1701−462 transitioned sharply from active accretion to quiescence in the final two weeks of the outburst. This last phase of the outburst was observed with *RXTE* and *Swift*, followed promptly by observations with *Chandra* and *XMM-Newton* in quiescence (see Fig. 2). The luminosity of the source dropped by three orders of magnitude in the final ≈12 days before entering quiescence. The end of the outburst is tightly constrained to a ≈4 day window between the last *Swift* observation and the first *Chandra* observation.

4 Spectral fitting

XTE J1701−462 was observed 12 times with *Chandra* and *XMM-Newton* during the first ~700 days of quiescence (see Fig. 1). This data set represents the best-sampled cooling curve of a NS transient to date. We fit all the spectra simultaneously with an absorbed two-component model consisting of a NS atmosphere model (thermal component) and a simple power law (non-thermal component). The thermal component is most likely due to emission from the NS surface; the origin of the non-thermal component is uncertain (see section 6). We assume a standard 1.4 solar mass NS with a radius of 10 km, and a distance of 8.8 kpc [4]. From our fit we infer the effective NS surface temperature, as well as both total and individual component fluxes, for each observation (see Fig. 3 in the right column).

Questions? Talk to Joel or send him an email at joelkf@mit.edu.
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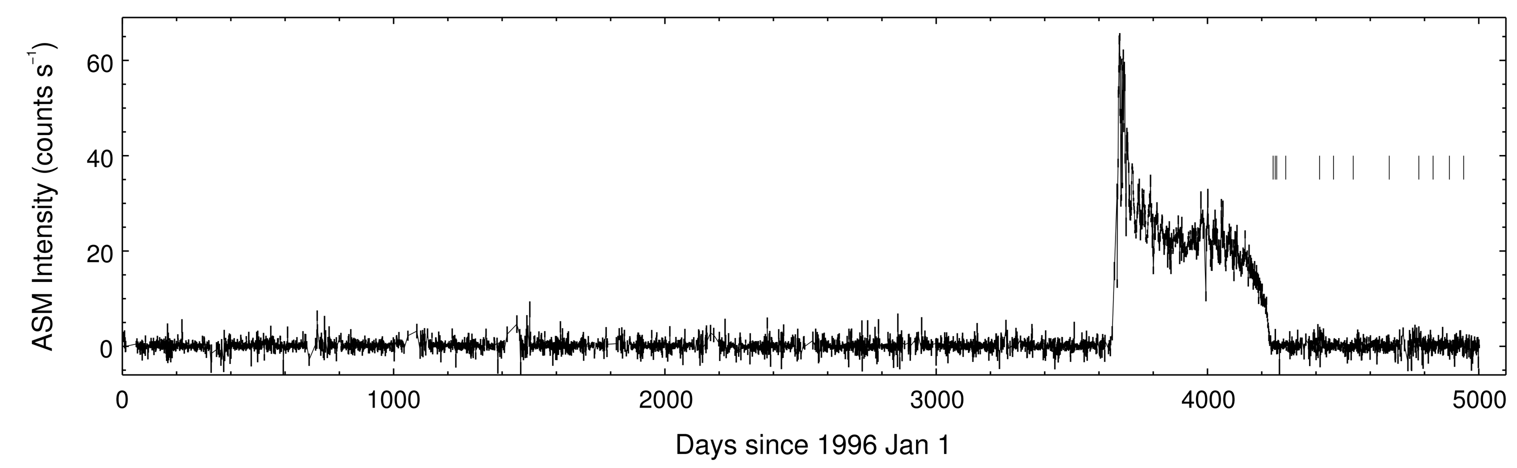

Figure 1: ASM light curve of XTE J1701-462 since the start of the *RXTE* mission. Vertical bars indicate the times of the 12 *Chandra* and *XMM-Newton* observations made during quiescence following the 2006-2007 outburst.

5 Cooling curves

The effective NS surface temperature was observed to decay rapidly during the first ~200 days of quiescence (see Fig. 3). We interpret this as the cooling of the NS crust towards equilibrium with the core. The interpretation of the data is complicated by a significant increase in temperature and luminosity ≈230 days into quiescence, which is inconsistent with the monotonic temperature decrease expected for a cooling NS (see further discussion in section 6). Excluding the 6th and 7th data points affected by the increase in temperature, we fit our temperature data with an exponential decay cooling curve with a constant offset (see middle panel in Fig. 3). The best-fit *e*-folding time is 112 ± 21 days with an offset temperature of 125.8 ± 1.0 eV. This is a much shorter timescale than that seen for other cooling transients observed after long-duration outbursts [5,6], and strongly indicates a highly conductive NS crust. The inferred surface temperature at the start of the quiescent phase is also considerably higher for XTE J1701−462 than other observed sources.

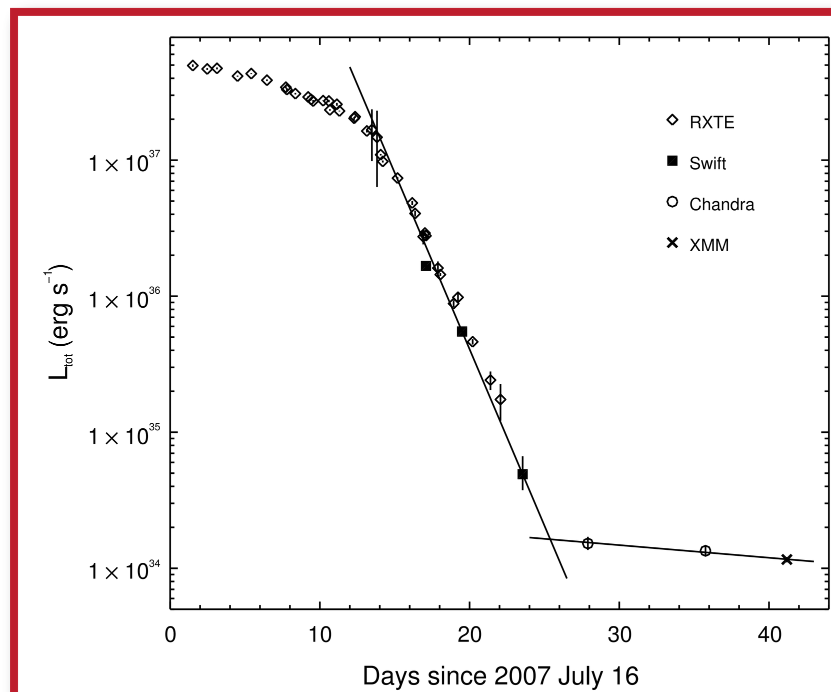

Figure 2: Total unabsorbed luminosity in the 0.5-10 keV band around the end of the outburst. The two lines are exponential decay curves through the last two *Swift* observations, and the first three *Chandra* and *XMM-Newton* observations. The intersection of these curves defines the end time of the outburst, t_0.

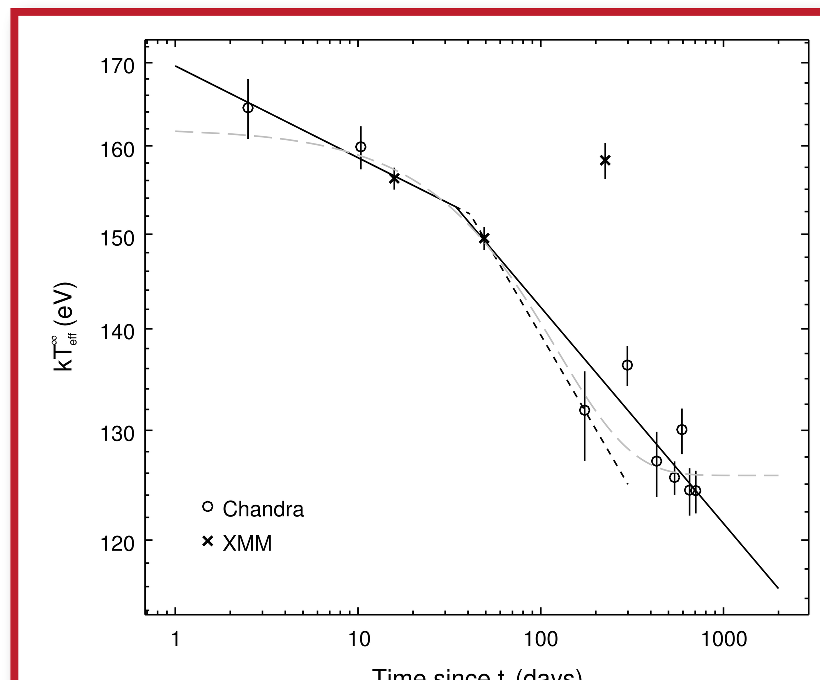

Figure 4: Effective surface temperature of the NS with best-fit cooling curves. The solid and short-dashed curves are broken power laws fitted to data points 1-5 plus 8-12, and points 1-5, respectively. The long-dashed gray curve is the best-fit exponential decay curve with a constant offset (also shown in Fig. 3).

We also fit our temperature data with a more physically motivated broken power-law cooling curve [7] (see Fig. 4). Data from other cooling sources have not shown evidence for a break in the cooling curve when fitted with power laws. In contrast, the XTE J1701−462 data show a clear indication of a break. However, the observed break is much earlier than the break predicted by theory [7], and may therefore represent a hitherto unrecognized structure in the theoretical cooling curves.

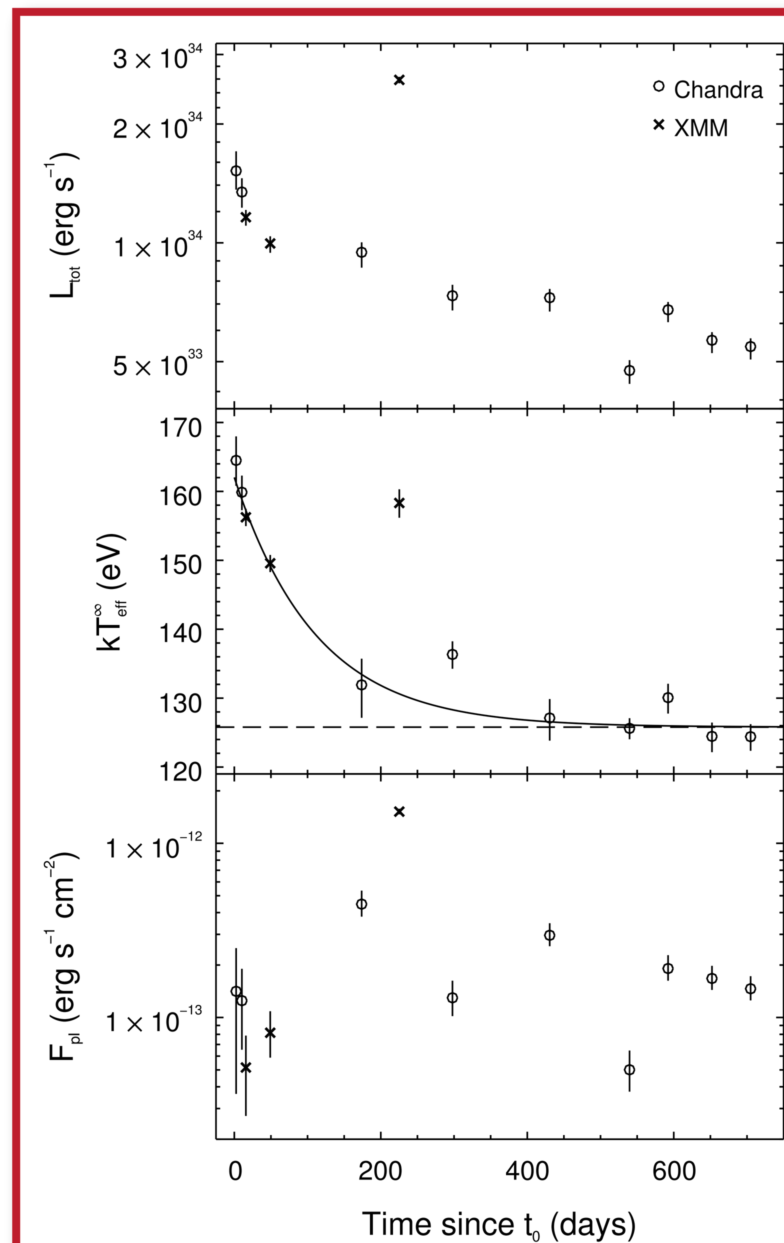

Figure 3: Total unabsorbed 0.5-10 keV luminosity (*top panel*), effective surface temperature of the NS (*middle panel*), and unabsorbed 0.5-10 keV power-law flux (*bottom panel*) during the post-outburst quiescent phase. The solid curve is the best-fit exponential decay cooling curve (excluding the 6th and 7th data points), and the dashed line indicates the best-fit constant offset to the decay.

Although the exponential decay cooling curve indicates that the NS crust in XTE J1701−462 has reached equilibrium with the core, the situation is less clear when considering the broken power law. The power-law curve may have flattened out already (as it is expected to eventually do [7]), or the source may still be cooling slowly. Additional observations are scheduled to investigate this. If the crust has indeed reached equilibrium at a surface temperature of ≈125 eV, then that would indicate an equilibrium bolometric thermal luminosity of ~5×10^{33} erg/s (for the best-estimate distance of 8.8 kpc), among the highest seen for a quiescent NS-LMXB. That might indicate a rather low-mass NS, since those are thought to have less efficient cooling mechanisms in their cores (see, e.g., [8]).

6 The non-thermal component

A non-thermal component has been seen in the spectra of many quiescent NS-LMXBs, but little is known about its origin. The spectra of XTE J1701−462 show a significant non-thermal (power-law) component, whose flux has varied irregularly throughout the quiescent phase by factors of up to ~30 (see bottom panel in Fig. 3), and on timescales as short as days. The fractional contribution of the power-law flux to the total flux has varied between ~5% and ~50%. As irregular variability on various timescales is a common characteristic of accretion, this may indicate that residual accretion of some sort is the cause of the non-thermal component in XTE J1701−462. We speculate that the increased temperature seen in the 6th and 7th observations is due to a spurt of (increased) accretion. This is supported by the fact that the 6th observation shows a much larger non-thermal flux than any other observation.

References: [1] Brown et al. 1998, ApJ, 504, L95 [2] Rutledge et al. 2002, ApJ, 580, 413 [3] Lin et al. 2009, ApJ, 696, 1257 [4] Lin et al. 2009, ApJ, 699, 60 [5] Cackett et al. 2006, MNRAS, 372, 479 [6] Cackett et al. 2008, ApJ, 687, L87 [7] Brown & Cumming 2009, ApJ, 698, 1020 [8] Yakovlev & Pethick 2004, ARA&A, 42, 169