



UvA-DARE (Digital Academic Repository)

Neutron star crust cooling in KS 1731-260

the influence of accretion outburst variability on the crustal temperature evolution

Ootes, L.S.; Page, D.; Wijnands, R.; Degenaar, N.

DOI

[10.1093/mnras/stw1799](https://doi.org/10.1093/mnras/stw1799)

Publication date

2016

Document Version

Final published version

Published in

Monthly Notices of the Royal Astronomical Society

[Link to publication](#)

Citation for published version (APA):

Ootes, L. S., Page, D., Wijnands, R., & Degenaar, N. (2016). Neutron star crust cooling in KS 1731-260: the influence of accretion outburst variability on the crustal temperature evolution. *Monthly Notices of the Royal Astronomical Society*, 461(4), 4400-4405. <https://doi.org/10.1093/mnras/stw1799>

General rights

It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations

If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: <https://uba.uva.nl/en/contact>, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

Neutron star crust cooling in KS 1731–260: the influence of accretion outburst variability on the crustal temperature evolution

Laura S. Ootes,¹★ Dany Page,² Rudy Wijnands¹ and Nathalie Degenaar^{1,3}

¹*Anton Pannekoek Institute for Astronomy, University of Amsterdam, Postbus 94249, NL-1090 GE Amsterdam, the Netherlands*

²*Instituto de Astronomía, Universidad Nacional Autónoma de México, 04510 México, D.F., Mexico*

³*Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*

Accepted 2016 June 28. Received 2016 June 6

ABSTRACT

Using a theoretical model, we track the thermal evolution of a cooling neutron star crust after an accretion-induced heating period with the goal of constraining the crustal parameters. We present for the first time a crust cooling model – NSCOOL – that takes into account detailed variability during the full outburst based on the observed light curve. We apply our model to KS 1731–260. The source was in outburst for ~ 12 yr during which it was observed to undergo variations on both long (years) and short (days–weeks) time-scales. Our results show that KS 1731–260 does not reach a steady state profile during the outburst due to fluctuations in the derived accretion rate. Additionally, long time-scale outburst variability mildly affects the complete crust cooling phase, while variations in the final months of the outburst strongly influence the first ~ 40 d of the calculated cooling curve. We discuss the consequences for estimates of the neutron star crust parameters, and argue that detailed modelling of the final phase of the outburst is key to constraining the origin of the shallow heat source.

Key words: accretion, accretion discs – stars: individual: KS 1731–260 – stars: neutron – X-rays: binaries.

1 INTRODUCTION

Neutron stars in low-mass X-ray binaries (LMXBs) accrete matter from their companions. Some sources accrete persistently, while others accrete episodically (transient sources). The length of an accretion episode is typically weeks to months. However, in quasi-persistent sources the accretion outburst lasts for $\gtrsim 1$ yr.

Large amounts of gravitational potential energy are released as matter falls on to the neutron star surface. The observed surface temperatures during accretion are of the order 10^7 K. If the interior temperature is lower, heat generated at the surface may flow inward. The accreted material is fused into heavier elements in the underlying ocean, producing heat that can raise the ocean’s temperature well above the surface temperature. This stops the inflow of gravitationally generated heat (Fujimoto et al. 1984; Miralda-Escude, Paczynski & Haensel 1990), while a fraction of the thermonuclear heat may still flow inward as long as the temperature gradient from the ocean towards deeper layers is negative. Finally, the accreted material is compressed to higher densities where electron captures, neutron emission, and pycnonuclear reactions result in the release of ~ 1 –2 MeV per accreted nucleon (Sato 1979; Haensel & Zdunik 1990). Most of this energy is released deep in the crust at

densities 10^{12-13} g cm $^{-3}$ where the pycnonuclear reactions take place. This energy heats up the region where the reactions occur (Miralda-Escude et al. 1990) and slowly flows into the stellar core.

This last mechanism is known as the deep crustal heating model and has been invoked to explain the observed high quiescent luminosities of neutron stars in transient LMXBs (Brown, Bildsten & Rutledge 1998). Even with short, but repeating, accretion outbursts deep crustal heating will heat up the core of the star until it reaches an equilibrium temperature (Brown et al. 1998; Colpi et al. 2001).

In quasi-persistent sources (and some normal transients), the effect of the deep crustal heating is strong enough that the crust is brought out of thermal equilibrium with the core (Rutledge et al. 2002). For an outburst with constant accretion rate that lasts years to decades, a steady state will be reached in the crust in which the amount of heat released in the crust is high enough to compensate the heat loss to the core and the surface (Brown & Cumming 2009; Page & Reddy 2013). Once the system returns to quiescence, the crust cools down until thermal equilibrium with the core is restored.

The time-scale of crustal heating and cooling depends on crustal microphysics (e.g. thermal conductivity and specific heat, which depend strongly on chemical composition) and macroscopic parameters (crust mass and thickness), as well as the outburst properties: accretion rate and outburst duration. During quiescence, the core temperature sets the quiescent base level. Rutledge et al. (2002) proposed that observations during the crust cooling period allow one

* E-mail: l.s.ootes@uva.nl

to probe the crustal physics of neutron stars. To date, crust cooling after an accretion outburst has been observed in eight sources (e.g. Wijnands et al. 2001, 2003; Fridriksson et al. 2010; Degenaar et al. 2013, 2014, 2015; Homan et al. 2014; Waterhouse et al. 2016).

During the past 15 yr various crust cooling models have been developed that explain the observed cooling curves based on the heat diffusion equations, which allows one to quantify the properties of the neutron star crust (e.g. Shternin et al. 2007; Brown & Cumming 2009; Page & Reddy 2013; Horowitz et al. 2015; Turlione, Aguilera & Pons 2015). While it was initially thought that accreting neutron stars would have amorphous crusts (Schatz et al. 1999; Brown 2000), modelling the observed cooling curves has revealed that they have relatively low impurity crusts instead, because the fast overall crust cooling time-scale can only be explained by high crustal conductivity (e.g. Shternin et al. 2007; Brown & Cumming 2009). Modern simulations of the crustal structure reconciled these high conductivities with theory and moreover, found that the impurity parameter is not constant throughout the crust, demonstrating a significant difference between the outer and inner crust (Horowitz, Berry & Brown 2007; Horowitz et al. 2015; Mckinven et al. 2016).

Comparing cooling observations with calculated cooling curves has also encountered a new problem. While for some sources the cooling can be modelled using the heat sources expected within the deep crustal heating model (e.g. Page & Reddy 2013; Degenaar et al. 2015), others are observed to be hotter than predicted in the earliest phase of the crust cooling period. The cooling observations of these sources can only be explained if there is an additional heat source in the outermost layers of the neutron star crust, which has been referred to as the shallow heat source (e.g. Brown & Cumming 2009; Degenaar, Brown & Wijnands 2011; Page & Reddy 2013; Deibel et al. 2015; Turlione et al. 2015; Waterhouse et al. 2016). For those sources that require additional shallow heat, the specific amount differs per source: in most sources 1–2 MeV nuc^{-1} is enough to explain the observations, while one source requires ~ 10 MeV nuc^{-1} (Deibel et al. 2015). It should be noted that additional heat sources at shallow depths in the crust were also proposed to explain certain observed phenomena during thermonuclear burning on accretion neutron stars (e.g. in ’t Zand et al. 2012; Linares et al. 2012; Deibel et al. 2016). Searches to find the origin of the shallow heat source are still in preliminary stages (e.g. Medin & Cumming 2014), and many of the suggested mechanisms are unable to provide additional heat up to 10 MeV nuc^{-1} (see discussion by Deibel et al. 2015).

Previous crust cooling studies modelled the outburst profile as a step function, assuming a constant accretion rate during the outburst. However, observed outburst light curves generally show large variations in X-ray luminosity, indicating that the accretion rate is not constant. Moreover, such step functions do not take into account any decrease in accretion rate during the last phase of the outburst when the source returns to quiescence. So far only two models have been presented in which accretion rate decay was taken into account (Page & Reddy 2013; Deibel et al. 2015).

In this Letter we present for the first time a model that takes into account outburst variability on both long and short time-scales, using the observed outburst profile. We apply our model to KS 1731–260. The source was in outburst for over 12 yr when it returned to quiescence in early 2001 (Wijnands et al. 2001, 2002). We chose this source because of its long observed cooling curve (Cackett et al. 2006, 2010), and because observations were carried out throughout the whole outburst. However, the number of observations in the first ~ 7 yr, as well as in the last 2 months, of the outburst is limited. We determine the effect of accretion fluctuations on the evolution of the thermal state of the neutron star crust

during the outburst and discuss the influence on the calculated cooling curves and the consequences for constraining neutron star crustal parameters. Additionally, we consider the uncertainties yielded by the limitations of the available outburst data.

2 CRUST COOLING MODEL

We model the thermal evolution of the neutron star crust during and after the outburst using an improved version of the cooling code NSCOOL (Page & Reddy 2013). The code solves the thermal evolution equations (energy transport and conservation) taking into account general relativistic effects. We make use of the A18+ δ v+UIX* equation of state (Akmal, Pandharipande & Ravenhall 1998) for the core and assume the original catalyzed crust to be fully replaced by accreted material as described by Haensel & Zdunik (2008). This model assumes the initial composition of the nuclear-burning ashes to be ^{56}Fe . The code integrates the thermal profile of the neutron star up to the outer boundary, defined at a density $\rho_b = 10^8 \text{ g cm}^{-3}$. To calculate the effective temperature T_{eff} from the boundary temperature $T_b(\rho_b)$ we use the accreted envelope models from Potekhin, Chabrier & Yakovlev (1997), where we allow the amount of light elements in the envelope (parametrized through their column density y_{light}) to be adjustable.

We assume that 1.93 MeV nuc^{-1} is released in the crust during an accretion outburst (Haensel & Zdunik 2008). An additional shallow heat source is defined with strength Q_{sh} between $\rho_{\text{sh,min}}$ and $\rho_{\text{sh,max}}$, where $\rho_{\text{sh,max}} = 5\rho_{\text{sh,min}}$ (similar to Deibel et al. 2015). The released amount of shallow heat is proportional to the accretion rate. We neglect the contribution of superfluid phonons to the crustal conductivity and only consider electron contribution. Electron scattering by ions and phonons is calculated following Gnedin, Yakovlev & Potekhin (2001) and by impurities as in Yakovlev & Urpin (1980). Impurities in the crust are parametrized by the impurity parameter Q_{imp} . Finally, we set a uniform (redshifted) temperature T_0 in the stellar interior prior to the onset of accretion as initial condition.

2.1 Modelling the accretion outburst

To take into account accretion variability during the outburst, we determine a time-dependent accretion rate based on the observational data. KS 1731–260 was discovered in 1989 August with *Mir-Kvant*, but reanalysis of older data revealed that source was already active on 1988 October 21 (Sunyaev et al. 1989). We adopt this date as the start of the outburst and used the observational data from TTM (*Mir-Kvant*; Aleksandrovich et al. 2002) and ART-P (*GRANAT*; Chelovekov, Grebenev & Sunyaev 2006), which cover the first ~ 7 yr of the outburst. As of 2006 January, the source was monitored with the *Rossi X-Ray Timing Explorer (RXTE)*. We obtained monitoring data from its All Sky Monitor (ASM)¹ and pointed observations with the Proportional Counter Array (PCA)². The source was no longer detected with the ASM in 2001 January (Wijnands et al. 2001), which was confirmed with pointed PCA observations and Galactic bulge scan observations (Markwardt 2000; Markwardt et al. 2000). The last PCA detection of the source was obtained on 2001 January 21 (Cackett et al. 2006), and the first non-detection was on 2001 February 7 (Wijnands et al. 2001). We adopt the latter date as end of the outburst, resulting in a total outburst duration of 12.3 yr.

¹ http://xte.mit.edu/ASM_lc.html

² http://asd.gsfc.nasa.gov/Craig.Markwardt/galscan/html/KS_1731-260.html

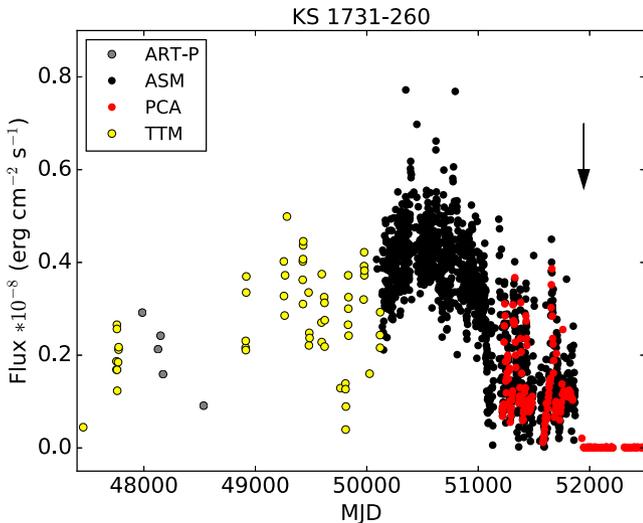


Figure 1. Light curve of KS 1731–260 during its 12 yr outburst in 2–10 keV flux units. The arrow indicates the day for which the first non-detection of the source was obtained. All points after this day are non-detections.

We converted the ART-P and TTM mCrab-fluxes into daily averaged 2–10 keV fluxes ($F(t)$), using a conversion factor $1 \text{ mCrab} = 2.2 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$. To convert the ASM (1.5–12 keV) and PCA (2–60 keV) count rates into 2–10 keV fluxes we used WebPIMMS,³ assuming a spectral power law with photon index 2 and a Galactic absorption column density $n_{\text{H}} = 1.3 \times 10^{22} \text{ cm}^{-2}$ (Cackett et al. 2006). Fig. 1 shows the combined light curve.

Next, we calculated a time-dependent mass accretion rate, $\dot{M}(t)$, using

$$\dot{M}(t) = \frac{1.8F(t)4\pi d^2}{\eta c^2}, \quad (1)$$

where c is the speed of light. We assumed a distance $d = 7 \text{ kpc}$ (Muno et al. 2000), a bolometric correction factor of 1.8, and took the fraction of the accreted mass that is converted into X-ray luminosity to be $\eta = 0.2$. We note that there are large uncertainties in the published bolometric correction factors (e.g. in’t Zand, Jonker & Markwardt 2007; Galloway et al. 2008). Our conclusions are not influenced by the exact value that is used.

We compute the accretion rate with a time accuracy of 1 d. If data from different telescopes overlap, we use PCA data if available; otherwise ASM data have priority over TTM data. For periods of missing data we estimate the accretion rate using linear extrapolation between the rates at the beginning and end of the data gap. This extrapolation is performed using 1 h time resolution. The main reason for this accuracy is to obtain a high-resolution estimate near the end of the outburst, as there are large gaps between the last two detections (61 d) and between the last detection and first non-detection (17 d). We obtain an average outburst accretion rate $\langle \dot{M} \rangle = 0.095 \dot{M}_{\text{Edd}}$ ($\dot{M}_{\text{Edd}} = 1.58 \times 10^{18} \text{ g s}^{-1}$).

3 RESULTS

When KS 1731–260 went into quiescence, observational campaigns with *XMM-Newton* and *Chandra* tracked the neutron star crust cooling (Wijnands et al. 2001, 2002; Cackett et al. 2006, 2010).

³ <http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl>

Using our model, we obtain a crust cooling curve and compare this with the observed temperatures. The code leaves several free parameters which we adjust to obtain a best fit of the observational data.

3.1 Time-dependent versus constant accretion rate

The left-hand panel in Fig. 2 shows the calculated cooling curves from two different models. The red curve (model 1) shows our best-fitting model when using a variable accretion rate as calculated from the observational data. Table 1 provides the parameters that we adopted in this model. The red curve in the inset in the figure shows the effective temperature as function of time during and after the outburst. The variations in temperature during the outburst are caused by variations in the accretion rate, as the outmost layers of the star (up to $\sim 3 \times 10^9 \text{ g cm}^{-3}$) have a nearly instantaneous response time, which can be observed from Video 1 (see online material).

The black cooling curve in Fig. 2 (model 2) shows the results of a model for which we have used the same input parameters as for model 1; the only difference being the fact that instead of a time-dependent accretion rate we have used a constant accretion rate (i.e. we assumed a step function as outburst profile). The accretion rate of model 2 is equal to the time-averaged accretion rate of model 1, $0.095 \dot{M}_{\text{Edd}}$, such that the total amount of accreted material is the same for the two models. Fig. 2 illustrates the strong effect of taking into account the observed variations in the light curve, especially in the first few hundred days of quiescence. The calculated cooling curve from model 2 does not provide a good fit to the observational data, except for the last few points. The parameters that are used in model 2 have to be modified to provide a good fit to the data points. Because the offset from the observational data is largest in the earliest phase of the cooling curve, this could be most easily achieved by decreasing the amount of shallow heating, Q_{sh} , to 0.6 MeV nuc^{-1} (i.e. about halve the original value; see Table 1). The amount of shallow heat regulates the temperature profile in the outer layers of the crust. Since the heat stored in the outermost layers starts diffusing outwards first after the end of the outburst, the temperature profile of the outer regions of the crust determine the initial part of the cooling curve (Brown & Cumming 2009).

The right-hand panel in Fig. 2 shows the temperature profile at the end of the outburst for model 1 (red) and model 2 (black). Model 2 reaches a steady state $\sim 8 \text{ yr}$ after the start of the outburst (see Video 1). However, if a time-dependent accretion rate is taken into account, KS 1731–260 never reaches a steady state profile due to the large accretion rate variations. Even the deepest crust layers ($10^{12-14} \text{ g cm}^{-3}$) are sensitive to variabilities on scales of years.

3.2 Long time-scale outburst variability

The amount of data that were obtained during the first $\sim 7 \text{ yr}$ of the outburst are limited, creating a high uncertainty on the estimated outburst accretion rates. Additionally, the exact start time of the outburst is unknown. To investigate the influence of long time-scale ($\gtrsim 1 \text{ yr}$) variations in the accretion rate in the first 7 yr of the outburst on the calculated cooling curves, we created four models, each assuming a different accretion rate in the first part of the outburst (top panel, Fig. 3). For all models, we assumed the same time-dependent accretion rate during the final $\sim 5 \text{ yr}$ of the outburst as in model 1. For model 3, we assumed no accretion during the first 7 yr (which one might have assumed if no data were available at all during this period). For models 4, 5, and 6, we assumed

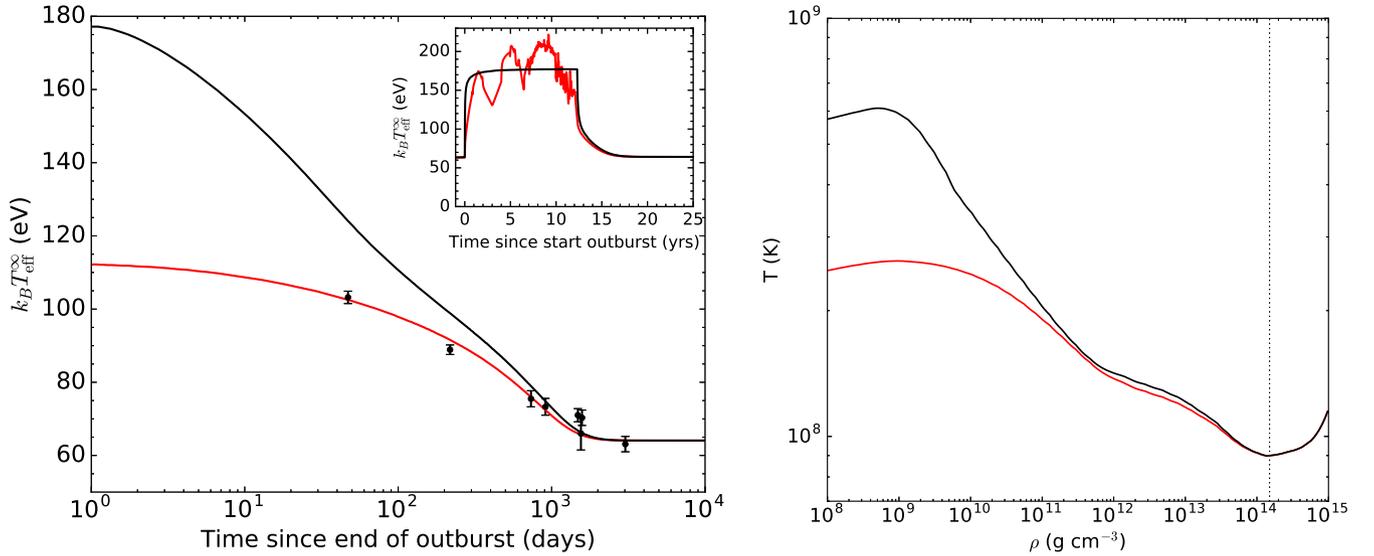


Figure 2. Left: calculated cooling curves for KS 1731–260 from model 1 (red, assuming a time variable accretion rate estimated from the observed outburst behaviour) and model 2 (black, assuming constant accretion rate). The inset shows the effective temperature during and after the accretion outburst as function of time since the start of the outburst. Right: calculated temperature profiles in the crust up to the boundary density $\rho_b = 10^8 \text{ g cm}^{-3}$ for models 1 and 2 at the end of the outburst. The dotted line indicates the crust–core boundary. Note that the temperature in the right-hand panel is the local, i.e. non-redshifted, temperature.

Table 1. Best-fitting parameters for model 1.

M (M_\odot)	R (km)	T_0 (K)	Y_{light} (g cm^{-2})	Q_{sh} (MeV)	$\rho_{\text{sh,min}}$ (g cm^{-3})	Q_{imp}
1.5	11.0	6.6×10^7	10^6	1.4	4×10^8	0.6

a constant accretion rate at a level of 50, 100, and 200 per cent, respectively, of the average accretion rate during this part of the outburst as determined from the data, which is $\dot{M}_{\text{ini}} = 0.087 \dot{M}_{\text{Edd}}$.

The four calculated cooling curves (Fig. 3, top panel) show small but significant differences that decrease until the crust has thermally relaxed ($\sim 2 \times 10^3 \text{ d}$ after the end of the outburst). We have again assumed the same model parameters for the neutron star as in model 1 (see Table 1). Since the difference in cooling curves is small for the considered accretion rates, this offset can be relatively easily compensated if one slightly adjusts one or two of the free parameters, with no explicit preference for which parameter(s).

3.3 Short time-scale outburst variability

The calculated cooling curve from model 5 does not show significant differences from model 1, indicating that short time-scale (days–weeks) variability during the first part of the outburst does not affect the temperature profile in the neutron star crust at the end of the outburst. To determine the effect of short time-scale variability during the final part of the outburst on the cooling curve, we created model 7. In this model we smoothed out all variations on short time-scales during the last 5 outburst years, and for the initial part we use again a constant accretion rate equal to the average accretion rate obtained from the corresponding part of the light curve.

The calculated cooling curve from model 7 provides a good fit of the observational data if we use the same model parameters as in model 1 (bottom panel, Fig. 3). However, the effective temperatures during the first $\sim 40 \text{ d}$ of quiescence are significantly higher than for model 1, because the smoothed fluxes provide a slight overestimation of the accretion rate during the decay phase of the

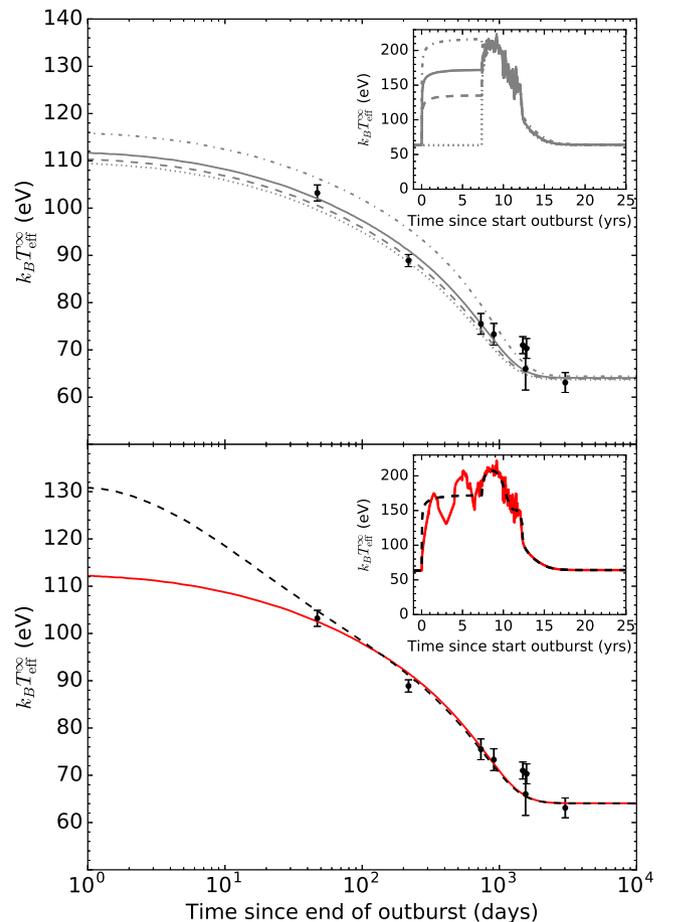


Figure 3. Same as Fig. 2, left-hand panel. Top: model 3 (dotted, initial $\dot{M} = 0$), model 4 (dashed, initial $\dot{M} = 0.5 \langle \dot{M}_{\text{ini}} \rangle$, with $\dot{M}_{\text{ini}} = 0.087 \dot{M}_{\text{Edd}}$), model 5 (solid, initial $\dot{M} = \langle \dot{M}_{\text{ini}} \rangle$), and model 6 (dash-dotted, initial $\dot{M} = 2.0 \langle \dot{M}_{\text{ini}} \rangle$). Bottom: models 1 (red) and 7 (black dashed, smoothed $\dot{M}(t)$ last 5 yr).

outburst; in model 1 the accretion rate decreases from $0.026\dot{M}_{\text{edd}}$ to $0.006\dot{M}_{\text{edd}}$ in the last 78 d of the outburst, compared to a decrease from $0.038\dot{M}_{\text{edd}}$ to $0.026\dot{M}_{\text{edd}}$ in model 7.

We tested for which period of time the short time-scale variations in accretion rate influence the cooling curve. For this specific source, we find that as long as the accretion rate during the last year of the outburst is determined from the obtained fluxes (while using the constant average accretion rate during the first ~ 11 yr), the calculated cooling curve does not differ significantly from the curve obtained from model 1, while for shorter periods it does.

Additionally, we tested the influence of the light-curve uncertainties in the last 78 d of the outburst (a 61-d gap between the last two detections and a subsequent 17-d gap until the first non-detection) using three scenarios: during the data gaps the accretion rate stayed constant compared to (1) the previous observation, (2) the next observation, and (3) the outburst ends directly after the last detection. We find that although all scenarios provide a good fit of the data if we use the same parameters as for model 1, the light-curve uncertainties provide temperatures up to 4 eV lower and 6 eV higher than for model 1 at the start of quiescence. This is comparable to the typical 1σ uncertainties from the observed surface temperatures.

4 DISCUSSION

We set out to investigate to what accuracy the accretion outburst of KS 1731–260 has to be modelled to constrain the neutron star crustal parameters from the cooling curve predicted by crust cooling models. Comparison of our calculated cooling curves based on different input outburst profiles shows that it is important to model the accretion rate and its variability during outburst as accurately as possible. We compared the results of a model that uses a step function as outburst profile (constant accretion rate) with a model that uses a time-dependent accretion rate and find that the two can give strongly different cooling curves for the same crustal parameters up to ~ 1000 d into quiescence. Since the difference is largest in the earliest phase of quiescence, the two models would likely lead to different constraints for the shallow heat source. All models of KS 1731–260 presented in this work require shallow heating to explain the large and rapid observed temperature decrease in quiescence.

Comparing the temperature profiles at the end of the outburst for the two models shows that if a constant accretion rate is assumed, the source will reach a steady state within ~ 8 yr after the start of the outburst (see Video 1), consistent with Brown & Cumming (2009). However, we find that a steady state is not reached when accretion variability is taken into account. This suggests that one cannot assume a steady state temperature profile as initial profile to calculate the cooling curve (Brown & Cumming 2009).

We tested the effects of long time-scale (years) variabilities on the calculated cooling curves, because the accretion rate during the initial part of this outburst is highly uncertain due to the limited available observational data (see Fig. 1). We found that variations in the average accretion rate during the first 7 yr of the outburst have a small, but non-negligible effect on the calculated cooling curve, indicating the importance of obtaining observations in all parts of the outburst. Because the differences in the cooling curves are constant throughout the cooling phase, uncertainties in the start time of the outburst and the average accretion rate during the first few years affect all crustal parameters. Consequently, if parts of the outbursts are missed it is essential that one models the time evolution of the temperature in the crust using different assumptions on the accretion

rate during the missed parts. Albeit these effects are source specific, uncertainties in the outburst profile of any source are expected to affect its cooling curve.

Short time-scale (days–weeks) variability in the first few years of the outburst has no effect on the calculated cooling curves. On the other hand, short time-scale variations in the accretion rate during the final phase of the outburst, especially the last year, do strongly affect the outcome of the cooling curve for KS 1731–260. The outer layers of the neutron star have a very short thermal response time. Consequently, these layers already start to cool during the decay phase of the outburst, as can be clearly seen from Video 1. As a result, the cooling curve starts at a significantly lower temperature when this effect is taken into account (see also Deibel et al. 2015). We find that even a small difference in modelling the decay phase of the outburst, and the uncertainties in the observational data of the last 78 d have a significant effect on the first ~ 40 d of the calculated cooling curve. Since the amount of shallow heating sets the temperature in the outermost layers of the crust, this parameter is very sensitive to variations in the decay phase of the outburst. If the decay of the outburst is not taken into account properly, the accretion rate in this phase is overestimated and the calculated cooling temperatures are initially too high. Consequently, the amount of shallow heating is likely to be underestimated.

The latter result has important implications for constraining the origin of the shallow heat source. Constraining the amount and depth of shallow heat is key to solving this gap in our current understanding of neutron star crusts. Our results show that to constrain the strength of the shallow heat source from crust cooling models it is stringent to observe and model the decay phase of the outburst in detail. Additionally, observations in the earliest phase of quiescence (the first month) are required.

Although our research only focuses on KS 1731–260, our findings apply to crust cooling models in general. For short-duration transients (outbursts of weeks–months), it is even more important to model variations in the outburst light curve, as these sources are further off from reaching a thermal steady state during outburst.

ACKNOWLEDGEMENTS

LSO and RW acknowledge support from an NWO Top Grant, Module 1, awarded to RW. DP is partially supported by the Mexican Conacyt (CB-2014-01, #240512). ND acknowledges support from an NWO Vidi grant and an EU Marie Curie Intra-European fellowship.

REFERENCES

- Akmal A., Pandharipande V. R., Ravenhall D. G., 1998, *Phys. Rev. C*, 58, 1804
- Aleksandrovich N. L., Revnivtsev M. G., Aref'ev V. A., Sunyaev R. A., Skinner G. K., 2002, *Astron. Lett.*, 28, 279
- Brown E. F., 2000, *ApJ*, 531, 988
- Brown E. F., Cumming A., 2009, *ApJ*, 698, 1020
- Brown E. F., Bildsten L., Rutledge R. E., 1998, *ApJ*, 504, L95
- Cackett E. M., Wijnands R., Linares M., Miller J. M., Homan J., Lewin W. H. G., 2006, *MNRAS*, 372, 479
- Cackett E. M., Brown E. F., Cumming A., Degenaar N., Miller J. M., Wijnands R., 2010, *ApJ*, 722, L137
- Chelovekov I. V., Grebenev S. A., Sunyaev R. A., 2006, *Astron. Lett.*, 32, 166
- Colpi M., Geppert U., Page D., Possenti A., 2001, *ApJ*, 548, L175
- Degenaar N., Brown E. F., Wijnands R., 2011, *MNRAS*, 418, L152
- Degenaar N. et al., 2013, *ApJ*, 775, 48

- Degenaar N. et al., 2014, *ApJ*, 791, 47
- Degenaar N. et al., 2015, *MNRAS*, 451, 2071
- Deibel A., Cumming A., Brown E. F., Page D., 2015, *ApJ*, 809, L31
- Deibel A., Meisel Z., Schatz H., Brown E. F., Cumming A., 2016, *ApJ*, preprint ([arXiv:1603.01281](https://arxiv.org/abs/1603.01281))
- Fridriksson J. K. et al., 2010, *ApJ*, 714, 270
- Fujimoto M. Y., Hanawa T., Iben I., Jr, Richardson M. B., 1984, *ApJ*, 278, 813
- Galloway D. K., Muno M. P., Hartman J. M., Psaltis D., Chakrabarty D., 2008, *ApJS*, 179, 360
- Gnedin O. Y., Yakovlev D. G., Potekhin A. Y., 2001, *MNRAS*, 324, 725
- Haensel P., Zdunik J. L., 1990, *A&A*, 227, 431
- Haensel P., Zdunik J. L., 2008, *A&A*, 480, 459
- Homan J., Fridriksson J. K., Wijnands R., Cackett E. M., Degenaar N., Linares M., Lin D., Remillard R. A., 2014, *ApJ*, 795, 131
- Horowitz C. J., Berry D. K., Brown E. F., 2007, *Phys. Rev. E*, 75, 066101
- Horowitz C. J., Berry D. K., Briggs C. M., Caplan M. E., Cumming A., Schneider A. S., 2015, *Phys. Rev. Lett.*, 114, 031102
- in't Zand J. J. M., Jonker P. G., Markwardt C. B., 2007, *A&A*, 465, 953
- in't Zand J. J. M., Homan J., Keek L., Palmer D. M., 2012, *A&A*, 547, A47
- Linares M., Altamirano D., Chakrabarty D., Cumming A., Keek L., 2012, *ApJ*, 748, 82
- Markwardt C., 2000, *AAS/High Energy Astrophysics Division*, 5, 1206
- Markwardt C. B., Swank J. H., Marshall F. E., in't Zand J. J. M., 2000, in Strohmayer T. E., ed., *Rossi2000: Astrophysics with the Rossi X-ray Timing Explorer*. NASA, Greenbelt
- Mckinven R., Cumming A., Medin Z., Schatz H., 2016, *ApJ*, 823, 117
- Medin Z., Cumming A., 2014, *ApJ*, 783, L3
- Miralda-Escude J., Paczynski B., Haensel P., 1990, *ApJ*, 362, 572
- Muno M. P., Fox D. W., Morgan E. H., Bildsten L., 2000, *ApJ*, 542, 1016
- Page D., Reddy S., 2013, *Phys. Rev. Lett.*, 111, 241102
- Potekhin A. Y., Chabrier G., Yakovlev D. G., 1997, *A&A*, 323, 415
- Rutledge R. E., Bildsten L., Brown E. F., Pavlov G. G., Zavlin V. E., Ushomirsky G., 2002, *ApJ*, 580, 413
- Sato K., 1979, *Progress Theor. Phys.*, 62, 957
- Schatz H., Bildsten L., Cumming A., Wiescher M., 1999, *ApJ*, 524, 1014
- Shternin P. S., Yakovlev D. G., Haensel P., Potekhin A. Y., 2007, *MNRAS*, 382, L43
- Sunyaev R. A. et al., 1989, in Hunt J., Battrick B., eds, *ESA Special Publication Vol. 296, Two Topics in X-Ray Astronomy, Vol. 1: X Ray Binaries. Vol. 2: AGN and the X Ray Background*. ESA, Noordwijk, p. 641
- Turlione A., Aguilera D. N., Pons J. A., 2015, *A&A*, 577, A5
- Waterhouse A. C., Degenaar N., Wijnands R., Brown E. F., Miller J. M., Altamirano D., Linares M., 2016, *MNRAS*, 456, 4001
- Wijnands R., Miller J. M., Markwardt C., Lewin W. H. G., van der Klis M., 2001, *ApJ*, 560, L159
- Wijnands R., Guainazzi M., van der Klis M., Méndez M., 2002, *ApJ*, 573, L45
- Wijnands R., Nowak M., Miller J. M., Homan J., Wachter S., Lewin W. H. G., 2003, *ApJ*, 594, 952
- Yakovlev D. G., Urpin V. A., 1980, *SvA*, 24, 303

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Video 1. video_1_Crust_Cooling_KS1731-260.mov
(<http://www.mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stw1799/-/DC1>)

Please note: Oxford University Press is not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

This paper has been typeset from a $\text{\TeX}/\text{\LaTeX}$ file prepared by the author.