

The Crust Cooling of Neutron Star with Varying Accretion Rate*

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Abstract: The transient neutron star (NS) low-mass X-ray binary provides a rare opportunity to study NS crust heating and cooling. Models of the quiescent light curve require additional heat in the shallow outer crust from an unknown source. Here we examine the crust cooling of NS with varying accretion rate to understand the effect of time-dependent accretion rate on crust cooling and shallow heating parameters with use of the open source code dStar. Our modeling indicates that variations of accretion rate during the early stage of outburst have a small effect on the theoretical crust cooling light curve, while variations in the final stage (days to months) of the outburst strongly affect the theoretical crust cooling light curve. The surface temperature of NS at the end of outburst with a time-dependent accretion rate is lower than that with constant accretion rate. As a result, more shallow heating is needed to fit the observational quiescent crust cooling light curve with time-dependent accretion rate. Our research focuses on MXB 1659-29 and MAXI J0556-332 which have different accretion time and shallow heating. We find that the results are consistent from these two sources.

Key words: low-mass X-ray binary; neutron star; accretion rate; crust cooling; shallow heating

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变化吸积率下中子星的壳冷却研究

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摘要: 暂现源中子星(NS)低质量X射线双星为研究NS壳加热和冷却提供了一个宝贵的机会. 模拟其宁静期的光变曲线需要在中子星的浅壳层加一个额外的未知热源. 通过开源的dStar程序, 探究时间依赖吸积率对中子星壳冷却以及浅壳层加热参数的影响. 研究表明: 爆发初期变化吸积率对壳冷却影响较小, 爆发期最后阶段吸积率的变化对壳冷却有较大的影响. 变化吸积率导致爆发结束后中子星表面的温度比常数吸积率下中子星表面温度低, 因此变化吸积率下需要提供更多的浅壳层加热来拟合爆发结束后的壳冷却观测. 研究了MXB 1659-29和MAXI J0556-332这两颗源, 它们对应不同的吸积时间以及浅壳层加热, 时间变化吸积率对这两颗源的壳冷却以及浅壳层加热参数的影响是一致的.

关键词: 低质量X射线双星; 中子星; 吸积率; 壳冷却; 浅壳层加热

0 Introduction

Neutron stars (NSs) are one of the compact objects whose mass and radius are typically $1.4 M_{\odot}$ and 10 km, and central density exceeds the nuclear density ($\rho_{\text{nuc}} \approx 2.8 \times 10^{14} \text{ g}\cdot\text{cm}^{-3}$). The core of NSs is covered by 1 km thick crust. The structure

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and composition of the crust of NSs play a crucial role in the evolution of their interior temperature and magnetic field. For instance, the crust properties are vital for a variety of observational phenomena, such as pulsar glitches, magnetar outbursts and thermonuclear X-ray bursts^[1–8].

Binaries consisting of a compact object and a normal star are called X-ray binaries. In X-ray binaries, matter falls onto a compact object from a companion star through the accretion disk, where the systems with the mass of the donor is less than about $1 M_{\odot}$ are called as low mass X-ray binaries (LMXBs)^[9]. Several NSs in LMXBs experience transient outburst during which matter from a disk around the NS is accreted onto its surface, the source is more luminosities with the X-ray luminosity $L_X \cong 10^{36} \sim 10^{39} \text{ erg}\cdot\text{s}^{-1}$ due to the high accretion rate, and its energy source is gravitational energy release. For ordinary transients, outbursts typically last for weeks to months, but some systems with active phases for years to even decades are called the quasi-persistent transients^[10–13]. During accretion, the continual compression of the crust induces electron capture, neutron emission and pycnonuclear reactions, the energy produced in these nuclear reactions is thought to be $1\sim 2 \text{ MeV/u}$ ^[14–16]. Since most energy is generated in the pycnonuclear reactions, this process is referred to as deep crustal heating. At quiescent phase, no (or only very little) matter is accreted onto the NS surface resulting in very faint luminosity with $L_q \cong 10^{31} \sim 10^{34} \text{ erg}\cdot\text{s}^{-1}$. The energy source of the quiescent X-ray luminosity is crustal heating during the outburst phase^[17–19].

In quasi-persistent transients and some normal transients, the effect of crustal heating will heat the crust out of thermal equilibrium with the core. When accretion halts, it might take years to even decades (depending on the properties of the crust) for the crust to cool down and reach equilibrium with the core again. To date, crust cooling after an accretion outburst has been observed in ten sources^[9,20–21]. Since the first crust cooling observation from KS 1731-260 in 2001^[22–23], various crust cooling models have been proposed to explain the observed cooling curves based on the heat diffusion equations, which provides a new avenue to probe the crustal physics of NS^[24–29].

Comparing cooling observations with theoretical cooling curves has encountered a new challenge. An additional heat source in the shallow outer crust is required to explain the temperatures observed in the first months of relaxation. In most sources, $1\sim 2 \text{ MeV/u}$ shallow heating is needed to explain the observations^[20,30], while one source requires $10\sim 17 \text{ MeV/u}$ ^[24]. Meanwhile, the depth of shallow heating is different from one source to another. For example, fits the light curve of MXB 1659-29 and KS 1731-260 need a shallow heat at depth of $10^8 \sim 10^9 \text{ g}\cdot\text{cm}^{-2}$ while models of the cooling curve of Aql X-1 require a shallow heat at depth of $10^{10} \text{ g}\cdot\text{cm}^{-2}$. The detailed magnitude and depth of shallow heating can be found in Table 1 of Ref [21]. The physical origin of shallow heating is as yet unknown. Searches to explain the origin of the shallow heating are still in preliminary stages, and many of the suggested mechanisms are unable to provide additional heat up to 10 MeV/u ^[20,31]. Besides, a constant accretion rate during the outburst was assumed in the previous crust cooling studies. However, the observed outburst light curves generally show large variations in X-ray luminosity, indicating that the accretion rate is not constant. As a result, Ootes, et al. studied the influence of accretion outburst variability on the crust temperature evolution in KS 1731-260^[32]. They showed that a time-dependent accretion rate could affect cooling curves strongly in the earliest phase of quiescence. Therefore, the time-dependent accretion rate would likely lead to different constraints for the shallow heat source. It's a pity that the previous works do not study the effect of time-dependent accretion rate on shallow heating detailedly.

In this work, we will take into account accretion variability on the crust cooling of neutron star, and then constraint on the depth and magnitude of shallow heating. We apply our model to MXB 1659-29 and MAXI J0556-332. The outburst I of MXB 1659-29 which was detected in 1999 lasted 2.5 a ^[33], it was the second source that the crust cooling was observed after KS 1731-260. The outburst II of MXB 1659-29 which was found in 2015 lasted 1.7 a . The crust cooling of these two sources requires 1 MeV/u shallow heating with constant accretion rate. While the outburst I of MAXI J0556-332 exhibited 16 months outburst after its discovery on January 11, 2011^[34], the crust cooling after its outburst needs very strong shallow heating as $6\sim 16 \text{ MeV/u}$ with constant accretion rate^[24]. We choose these two sources because of their different outburst duration and shallow heating. We explore the effect of time-dependent accretion rate on the crust cooling of these two sources and the consequences for constraining the shallow heating parameters.

1 Crust thermal relaxation model of accreting neutron star

In this section, we describe the crust thermal relaxation model of accreting NS with the use of the thermal evolution co-

de dStar. We will first give the basic equations for the thermal evolution of the crust of NS and then show our physical inputs.

1.1 Basic equations for the thermal evolution of the crust of neutron star

The structure of neutron star can be solved by the general-relativistic equations^[35]:

$$\frac{dr}{d\ln P} = -\frac{P}{\rho g}(1+z)^{-1} \quad (1)$$

$$\frac{dM}{d\ln P} = -4\pi r^2 \frac{P}{g} \quad (2)$$

$$\frac{d\phi}{d\ln P} = -\frac{P}{\rho} \quad (3)$$

where $1+z = [1 - 2GM/(rc^2)]^{-1/2}$ is the gravitational red-shift factor, gravitational acceleration $g = GM(1+z)/r^2$. ρ and M represent the density of mass-energy and gravitational mass, respectively. ϕ and P are potential and pressure, respectively.

The general relativistic heat diffusion equations can be written as^[24,30]:

$$C \frac{\partial}{\partial t} (T e^{\phi/c^2}) = e^{2\phi/c^2} (\epsilon_{\text{nuc}} - \epsilon_{\nu}) - \frac{1}{4\pi r^2 \rho (1+z)} \frac{\partial}{\partial r} (L e^{2\phi/c^2}) \quad (4)$$

$$L e^{2\phi/c^2} = -\frac{4\pi r^2 K e^{\phi/c^2}}{1+z} \frac{\partial}{\partial r} (T e^{\phi/c^2}) \quad (5)$$

where C is the specific heat, ϵ_{nuc} is the nuclear heating emissivity, ϵ_{ν} is neutrino emissivity, K is the thermal conductivity, T and L represent the local temperature and luminosity, respectively.

The above equations (1)~(5) can be solved numerically using the method of lines^[24,30].

1.2 Physical inputs

Neutrino emissivities ϵ_{ν} include electron-nucleus bremsstrahlung, electron-positron pair, photo and plasmon processes^[36-37]. Nuclear heating emissivities ϵ_{nuc} is produced by non-equilibrium nuclear reactions which deposit 0.2 MeV/u in the outer crust^[38] and 1.5 MeV/u in the inner crust^[14-16]. In NSs that require extra heating to fit their quiescent light curves, we include the additional nuclear heating emissivity of $\epsilon_{\text{nuc}} = \dot{m} Q_{\text{sh}}$ proportional to the accretion rate \dot{m} ^[24], where Q_{sh} is shallow heat source, expressed in MeV/u. For example, the NS transients MXB 1659-29 and KS 1731-260 require $Q_{\text{sh}} \approx 1$ MeV/u to reproduce their quiescent light curves with constant accretion rate^[30], while the hottest NS transient MAXI J0556-332 requires $Q_{\text{sh}} \approx 6\sim 16$ MeV/u^[24-25]. The temperature in the neutron star ocean T_{b} is mapped to the photosphere temperature T_{eff} using the envelope models with a helium top-layer and iron bottom-layer, where T_{b} is set at a column depth $y = 10^{10}$ g·cm⁻². The shallow heat source is deposited over the range $y = y_{\text{h}}/3 - y_{\text{h}} \times 3$ following Deibel, et al.^[24], where y_{h} is as the center of the shallow heat. The impurity parameter which is important to determine the thermal conductivity (K) of the crust is given by

$$Q_{\text{imp}} \equiv \frac{1}{n} \sum_i^h n_i (Z_i - \langle Z \rangle)^2 \quad (6)$$

where n_i is the number density of the nuclear species with Z_i number of protons, $\langle Z \rangle$ is the average proton number of the crust composition. One can find the details of the microphysics of the crust from Ref [30].

2 Accretion dependent behavior of crust cooling light curves

As described in the above section, we can numerically simulate the thermal evolution of the crust of NS. Here, we investigate the impact of time-dependent accretion rate on the crust cooling and heating of MXB 1659-29 and MAXI J0556-332.

2.1 The light curve of MXB 1659-29 with varying accretion rate

To fit the cooling light curve of MXB 1659-29 (outburst I), we assume that NS with $M = 1.6 M_{\odot}$, $R = 10$ km accreted at the constant accretion rate $\dot{M} = 1 \times 10^{17}$ g·s⁻¹ for 2.5 a, which is referred to Model I. Then, we set the accretion rate as a function of time for Models II, III and IV. The left panel in Fig 1 shows the accretion rate as a function of time for four different models. The right panel in Fig 1 shows the calculated cooling curves. The black curve (Model I) shows our best fit model when using a constant accretion rate as calculated from the observational data.

Table 1 provides the parameters that we adopted in Model I. The colored curves (Models II, III and IV) show the results of three models for which we have used the same input parameters for Model I, the only difference being the fact that instead of a constant accretion rate we have used a time-dependent accretion rate. The accretion rate of Model I is equal to the time-averaged accretion rate of Models II, III and IV.

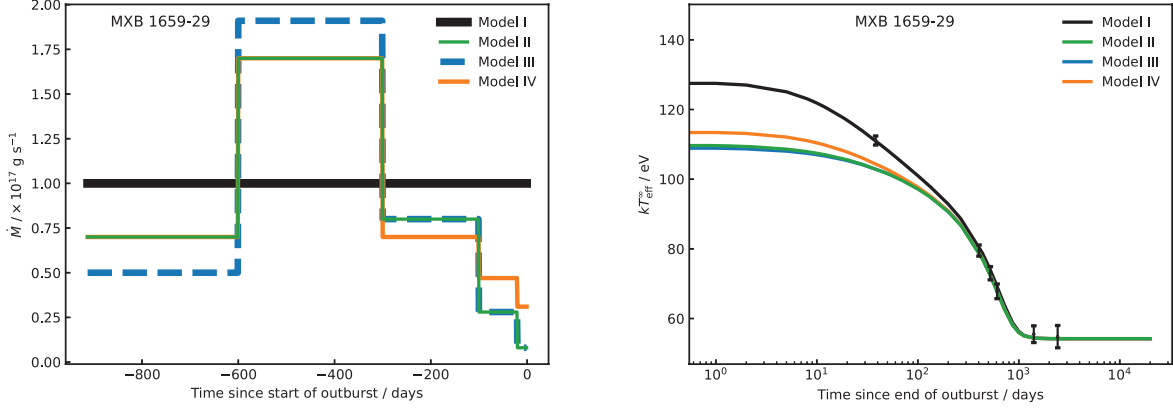


Fig 1 The accretion rate of MXB 1659-29 as a function of time since the start of the outburst (left) and calculated cooling curves for MXB 1659-29 from Models I, II, III and IV (Right).

Note: Model I (black) is constant accretion rate, Model II (green, assuming time-dependent accretion rate), Model III (blue, the accretion rate is different from Model II at the start of outburst) and Model IV (orange, the accretion rate is different from Model II at the end of outburst) are three models of time-dependent accretion rate.

Table 1 Fitting parameters of MXB 1659-29 with constant accretion rate

M/M_{\odot}	R/km	$T_c/\times 10^7 \text{ K}$	Q_{imp}	$y_{\text{light}}/\times 10^8 \text{ g}\cdot\text{cm}^{-2}$
1.6	12	2.9	2.6	1

As shown in the right panel of Fig 1, the accretion rate variations have strong effect on the quiescent light curve, especially in the first few hundred days of quiescence. The effective surface temperature of NS at the end of outburst for a time-dependent accretion rate is lower than that with a constant accretion rate. By comparing Models III and IV with Model II, we found that the accretion rate variation at the early phase (Model III) of the outburst has small effect on the crust cooling curve, while the variations of accretion rate in the final phase of the outburst (Model IV) strongly affect the calculated cooling curve, our results are consistent with Ootes, et al. [32].

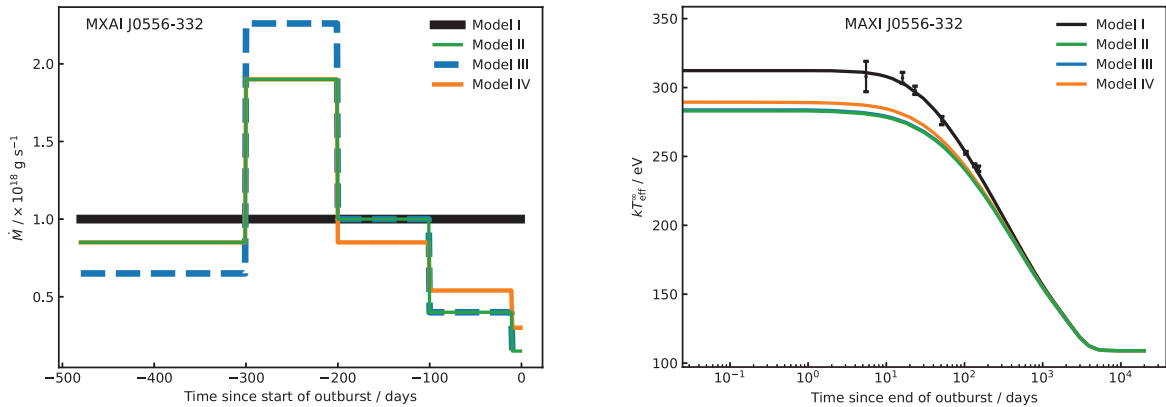


Fig 2 The accretion rate of MAXI J0556-332 as a function of time since the start of the outburst (left) and calculated cooling curves for MAXI J0556-332 from Models I, II, III and IV (right)

Note: Model I (black) is constant accretion rate, Model II (green, assuming time-dependent accretion rate), Model III (blue, the accretion rate is different from Model II at the start of outburst) and Model IV (orange, the accretion rate is different from Model II at the end of outburst) are three models of time-dependent accretion rate.

2.2 The light curve of MAXI J0556-332 with varying accretion rate

In this section, we study the light curve of the hottest NS transient MAXI J0556-332 (outburst I) with varying accretion rate. Our thermal evolution model of MAXI J0556-332 uses NS with $M = 1.5 M_{\odot}$ and $R = 11$ km that accreted for 16 months, Model I corresponds to a constant accretion rate of $\dot{M} \approx 1 \times 10^{18} \text{ g}\cdot\text{s}^{-1}$, Models II, III and IV correspond to varying accretion rate. The left panel of Fig 2 shows the accretion rate of MAXI J0556-332 as a function of time since the star of outburst. The right panel of Fig 2 shows the calculated cooling curves of MAXI J0556-332. The black curve (Model I) shows our best fit model when using a constant accretion rate as calculated from the observational data. Table 2 shows the parameters that we adopted in Model I. Similarly, the light curves with Models II, III and IV show the results with varying accretion rate. The only difference is the fact that instead of a constant accretion rate in Model I we have used a time-dependent accretion rate in Models II, III and IV.

Although the accretion rate, the outburst duration and shallow heating of MAXI J0556-332 are different from MXB 1659-29. The effect of time-dependent accretion rate on the cooling curves are similar for these two sources (see the right panels of Fig 1 and Fig 2). This suggests that the effect of accretion rate variations on crust cooling of NS transients are in general.

Table 2 Fitting parameters of MAXI J0556-332 with constant accretion rate

M/M_{\odot}	R/km	$T_c/\times 10^7 \text{ K}$	Q_{imp}	$y_{\text{light}}/\times 10^8 \text{ g}\cdot\text{cm}^{-2}$
1.5	11	12	1	1

2.3 The influence of time-dependent accretion rate on shallow heating

The time-dependent accretion rate affect cooling curves strongly in the earliest phase of quiescence. As a result, the time-dependent accretion rate would likely lead to different constraints for the shallow heat source. Here, we investigate the impact of time-dependent accretion rate on the shallow heating parameters (magnitude Q_{sh} and depth P_{sh}).

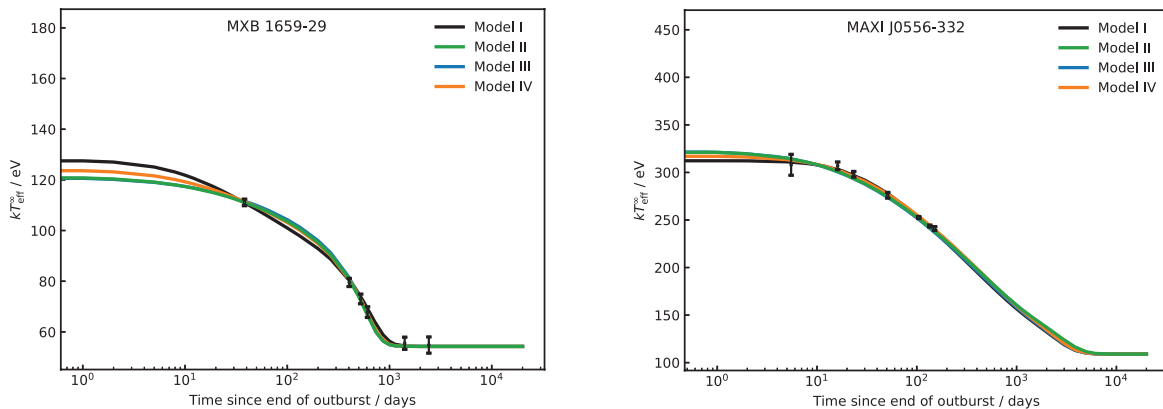


Fig 3 The fitted light curves of MXB 1659-29 and MAXI J0556-332 with time-dependent accretion rate

The fitted light curves of MXB 1659-29 and MAXI J0556-332 with time-dependent accretion rates are shown in Fig 3. As the temperature with Models II, III and IV (accretion rate variability) at the beginning of the cooling stage is lower than that with Model I (constant accretion rate). To fit the observed data, more shallow heating will be needed. The magnitude (Q_{sh}) and depth (P_{sh}) of shallow heating for the four models are shown in Table 3. We see that Q_{sh} with time-dependent accretion rate (Models II, III and IV) is bigger than that with constant accretion rate, and the depth (P_{sh}) of shallow heat with time-dependent accretion rate is shallower than that with constant accretion rate. In our cooling models, the magnitude (Q_{sh}) of shallow heating is changed by maximally $\lesssim 54\%$ for MXB 1659-29 and $\lesssim 41\%$ for MAXI J0556-332. The depth (P_{sh}) of shallow heating is changed by maximally $\lesssim 50\%$ for MXB 1659-29 and $\lesssim 75\%$ for MAXI J0556-332. As MAXI J0556-332 need more shallow heat source than MXB 1659-29, the absolute change of the shallow heat parameters of MAXI J0556-332 are more obvious than that of MXB 1659-29. However, to understand the unknown shallow heat source better, maybe a statistical method that needs more observations of crust cooling of soft X-ray transients is needed^[39].

Table 3 Shallow heating parameters for MXB 1659-29 and MAXI J0556-332 with time-dependent accretion rate

Model	MXB 1659-29		MAXI J0556-332	
	$Q_{\text{sh}}/\text{MeV}\cdot\text{u}^{-1}$	$\lg P_{\text{sh}}/\text{erg}\cdot\text{cm}^{-3}$	$Q_{\text{sh}}/\text{MeV}\cdot\text{u}^{-1}$	$\lg P_{\text{sh}}/\text{erg}\cdot\text{cm}^{-3}$
I	0.85	27.0	6.1	28.1
II	1.30	26.8	8.5	27.6
III	1.31	26.7	8.6	27.5
IV	1.20	26.9	7.9	27.9

3 Conclusion

Accretion outbursts have been observed for many NSs in low-mass X-ray binaries, nonequilibrium nuclear reactions during active accretion heat the NS crust out of thermal equilibrium with the core^[40]. When accretion stops, the crust cools toward thermal equilibrium with the core. Crust cooling has been observed as a quiescent X-ray light curve for ten sources. We explore the effect of time-dependent accretion rate on the crust cooling of NS in this work. Since the temperature at the end of outburst with time-dependent accretion rate is lower than that with constant accretion rate, our models lead to different constraints for the shallow heat source. More shallow heating will be needed to fit the cooling light curve for the same source if an accretion outburst variability is taken into account. We apply our thermal evolution model to two most well-studied NS transients MXB 1659-29 and MAXI J0556-332, the effect of time-dependent accretion rate on crust cooling and shallow heating are similar. The results have important implications for constraining the physical origin of the shallow heat source.

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