Modeling the thermal properties of quasi-persistent neutron star X-ray binaries

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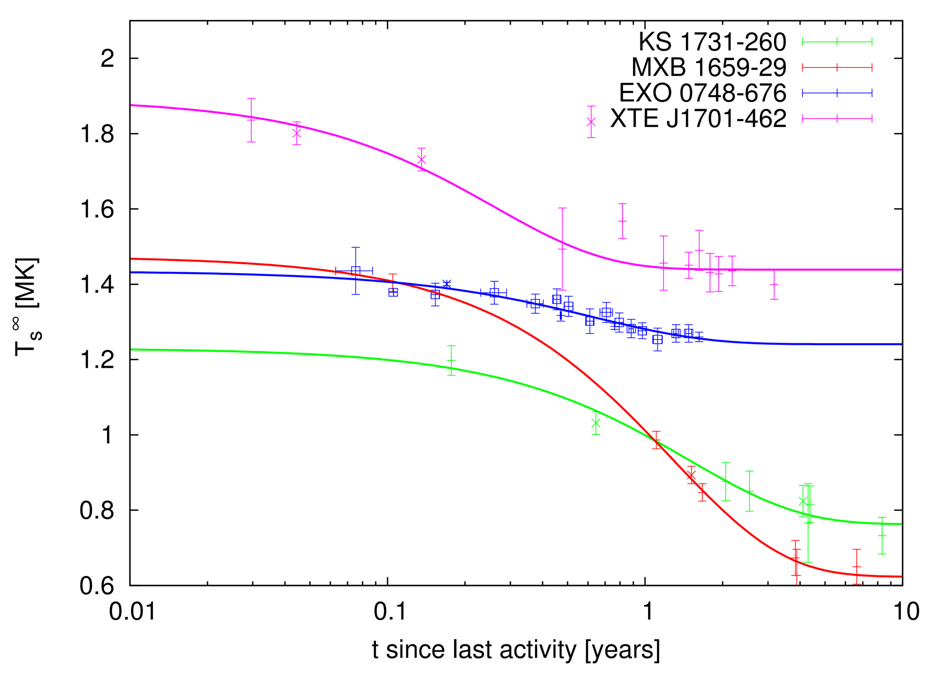
Abstract

We develop a model for the thermal evolution of the four quasi-persistent X-ray transients in both the active and quiescent phases based on an up-to-date description of the microphysics in the outer layers of the neutron star. The burning of the accreted matter that generates heat at low densities is taken into account.

Context

The four quasi-persistent X-ray transients (QPXRTs) consist of a neutron star (NS) that accretes matter from a low-mass companion star. They exhibit active phases lasting from years to decades when the NS accretes ($L_X \sim 10^{36} - 10^{39}$ erg s^{-1}) and quiescent phases when accretion significantly decreases ($L_X < 10^{34}$ erg s^{-1}).
In the deep-crustal heating scenario [1], the accreted matter undergoes a series of nuclear reactions, eg. [2], while it sinks deeper into the crust under the weight of the newly-accreted material. The reactions produce heat that is at the origin of the thermal relaxation observed just after accretion stops. Therefore, the modeling of the thermal evolution of these QPXRTs enables to put constraints on the internal properties of neutron stars.
The thermal relaxation of KS $1731-260$ exclude fast cooling due to enhanced neutrino emission in the core and is consistent with a crystalline crust with superfluid neutrons [3]. The thermal relaxations of KS $1731-260$ and MXB $1659-29$ are consistent with an impurity parameter Q_{imp}, which describes the distribution of nuclide charge numbers, of the order of 1 [4].

Relaxation time scales



Thermal relaxation of the 4 QPXRTs. Observational data from [5], [6], [7], [8]. Note the logarithmic scale in time.

The best-fit by an exponential decay of the thermal relaxation of the four QPXRTs gives the following time-scales :

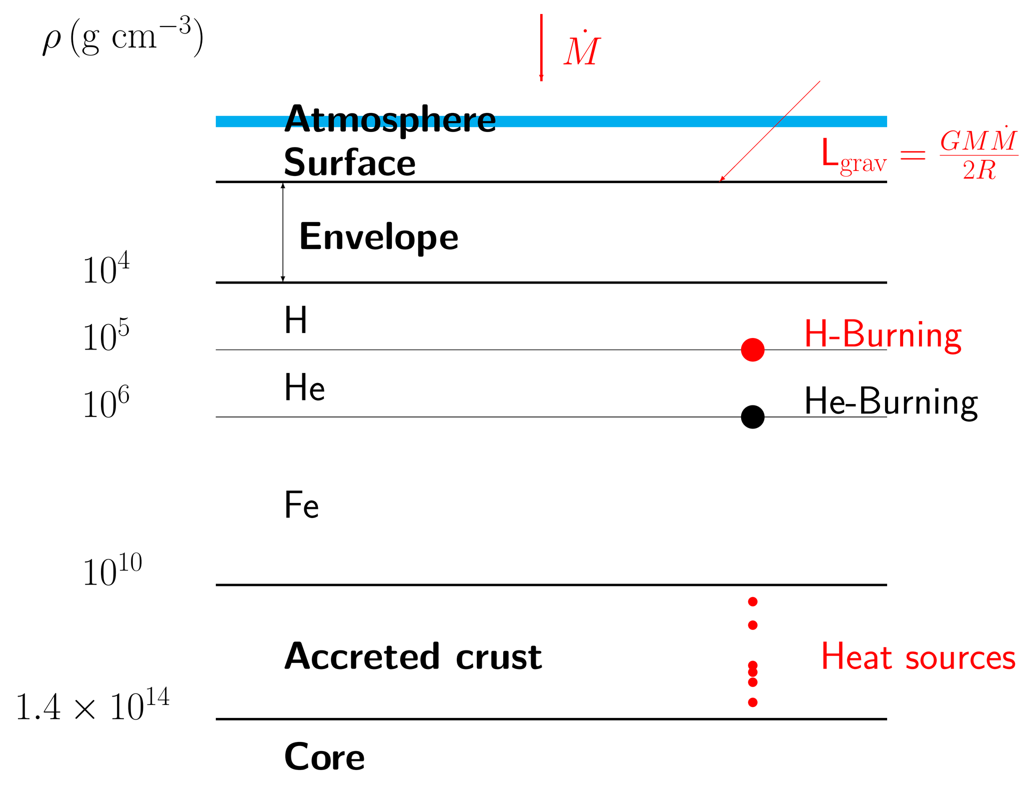
Sources	τ (d)
KS $1731-260$	540 ± 125
MXB $1659-29$	465 ± 35
EXO $0748-676$	230 ± 60
XTE J$1701-462$	95 ± 15

The models that have been used so far are unable to simulate the fast thermal relaxation of EXO $0748-676$ and XTE J$1701-462$. These sources suggest that there exist heat sources at densities lower than the ones that have been considered so far.

Neutron star model

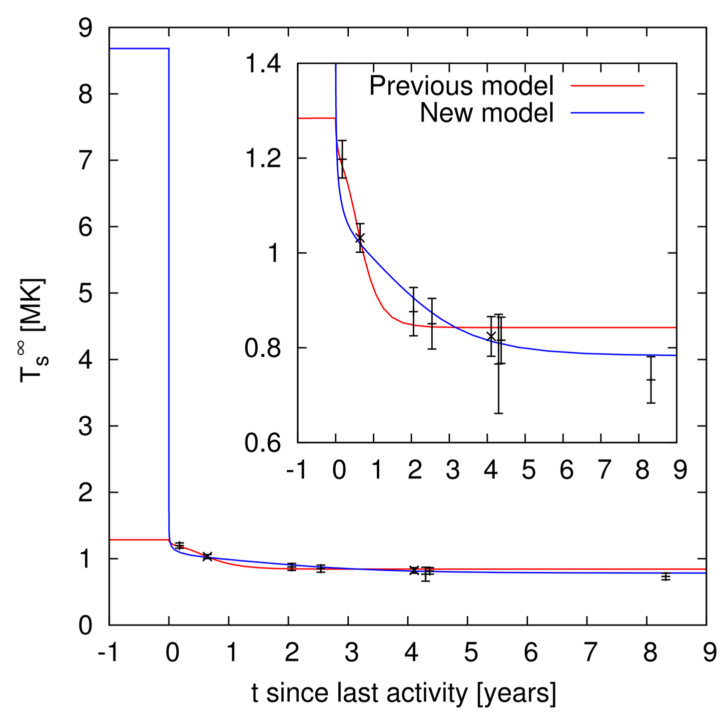
We consider a 1.4 M$_\odot$ NS with an EoS for the accreted crust as described in [2] and for the core in [9].
Superfluidity effects are included. The neutron $^1S_0$ and $^3P_2$ gaps are taken from [10] and [11] (gap a) respectively and the proton $^1S_0$ gap from [12]. The Cooper pair breaking and formation processes are taken into account with the vector part put to zero [13].
The thermal evolution is calculated with the `NSCool` code [14] for an accreting phase lasting t_{acc}, with a step-like accretion rate $\dot{M}$.
In previous models [3], [4] the heat equation is solved from the center down to a density of 10^{10} g cm^{-3} and a model of atmosphere, eg. [15], gives the temperature at the surface. Therefore the burning of the accreted matter at lower density is not taken into account.

Envelope model

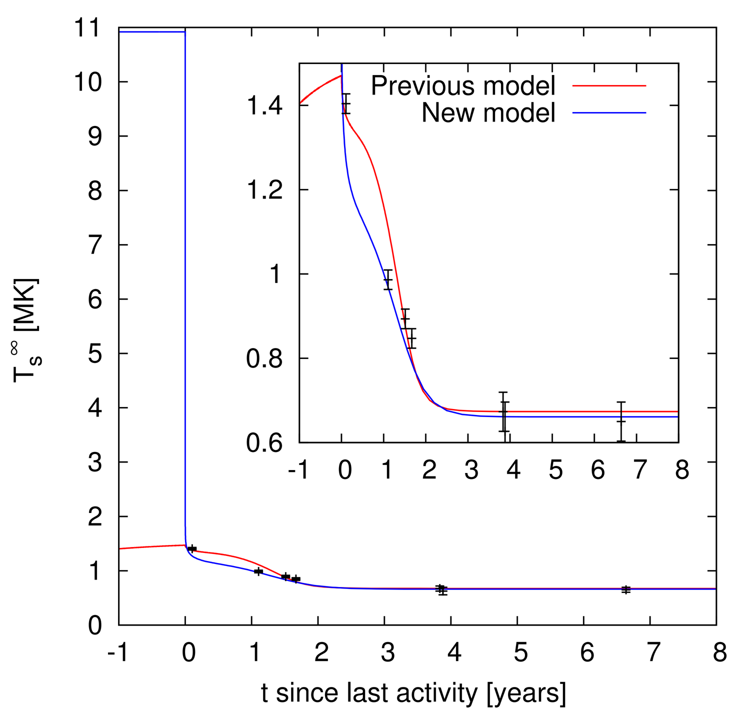


In our new model, when the NS accretes, the gravitational energy of the accreted material is included at the surface. We use a preliminary model of atmosphere with non-degenerate electrons [16]. The burning of the accreted hydrogen releases 5 MeV per accreted particle at a density of 10^5 g cm^{-3}. The helium that is produced is assumed to burn into bursts with very short time scales. Thus, the heat release due to the helium burning is neglected and an iron layer extends for densities between 10^6 and 10^{10} g cm^{-3}.
The thermal conductivity and the specific heat for an envelope with a fully ionized nonmagnetic electron-ion plasma are calculated from [17] and [18] respectively. The neutrino losses in the envelope are neglected since they are negligible compared to the heat release [19].

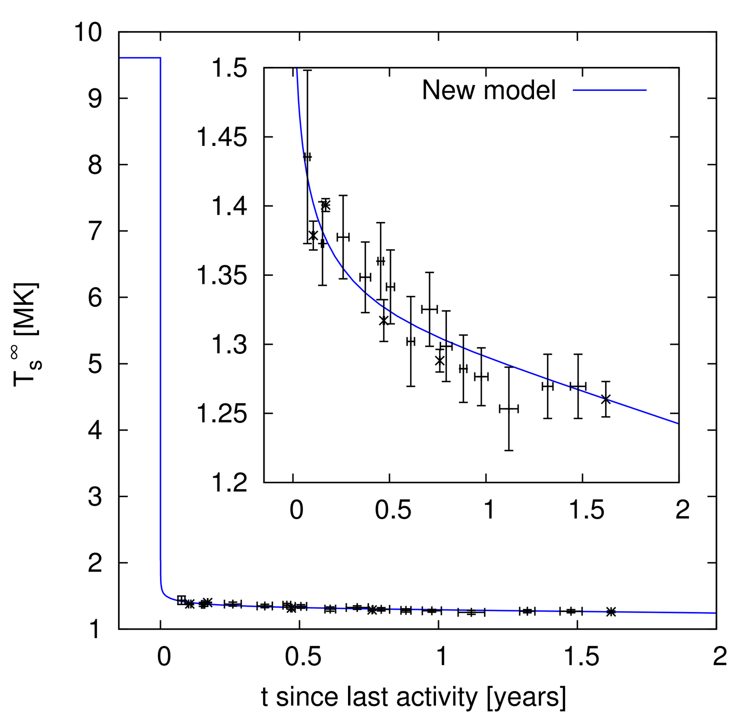
Modeling of the thermal relaxation of the 4 QPXRTs



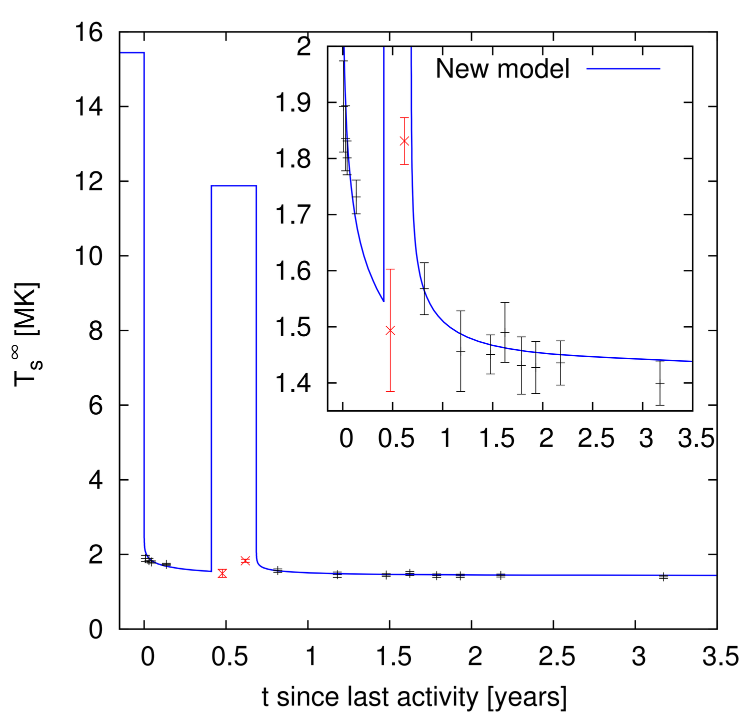
KS 1731-260 : $t_{acc} = 12.5$ yrs. Previous model : $\dot{M} = 2.6 \times 10^{-9}$ M$_\odot$ yr^{-1}. New model : $\dot{M} = 2 \times 10^{-9}$ M$_\odot$ yr^{-1}.



MXB 1659-29 : $t_{acc} = 2.5$ yrs. Previous model : $\dot{M} = 4 \times 10^{-9}$ M$_\odot$ yr^{-1}, Qimp $= 2$. New model : $\dot{M} = 5 \times 10^{-9}$ M$_\odot$ yr^{-1}, Qimp $= 0$.



EXO 0748-676 : $t_{acc} = 26$ yrs. New model : $\dot{M} = 3 \times 10^{-9}$ M$_\odot$ yr^{-1}.



XTE J1701-462 : see text below. New model : $\dot{M}_1 = 2 \times 10^{-8}$ M$_\odot$ yr^{-1}, $\dot{M}_2 = 7 \times 10^{-9}$ M$_\odot$ yr^{-1}.

XTE J$1701-462$ exhibits a sudden increase in temperature in the relaxation stage that is believed to originate from a sudden spur of accretion. The high power-law contribution to the total flux in the observations 5 and 6 (in red in the figure) shows that the accretion had already started. Therefore, these points will not be fitted. Thus, we consider that after accreting during $t_{acc1} = 1.6$ yrs, XTE turns into quiescence for $t_{quies} \sim 150$ days before accretion starts again for $t_{acc2} \sim 100$ days.

Perspectives

Our model simulates the thermal relaxation of all QPXRTs for a 1.4 M$_\odot$ NS.
Future work involves the inclusion of the temperature and density dependence of the hydrogen and helium burning. In collaboration with A. Różańska (CAMK), we will also use a realistic model of atmosphere for an accreting NSs, that will provide the spectral properties in the accreting phase. Therefore we will simulate the thermal evolution of the QPXRTs in both the accreting and quiescent phases. Our model could be extended to the study of normal transients.

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