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QUIESCENT THERMAL EMISSION OF NEUTRON STARS IN LMXBs

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Recent monitoring of the quiescent thermal emission from NSs in low mass X–ray binaries (LMXBs) after active periods (bursts) opened a new view to the physics of dense matter. Theoretical modeling of the thermal relaxation of the crust may be used to establish constraints on the thermal conductivity of matter, depending on the accretion rate. We present here cooling curves obtained from numerical simulations that fit the light curves for two sources (KS 1731-260, MXB 1659-29). We estimate the model parameters (accretion rate, thermal conductivity) that match the data and compare our results with previous constraints of neutron star crust properties in LMXBs.

Keywords: Neutron stars; X–rays; nuclear heating.

1. Introduction

Low-mass X–ray binaries (LMXBs) consist of either a neutron star (NS) or a black hole that accretes matter from a low-mass companion star. These systems are most of the time in a quiescent state where little accretion occurs and low X–ray luminosity $< 10^{34}\,\mathrm{erg\,s^{-1}}$. Periodically, the mass accretion rate rises with a corresponding increase in luminosity $\sim 10^{36}$–$10^{39}\,\mathrm{erg\,s^{-1}}$ (outburst). The material accreted during the recurrent outbursts compresses the crust, induces nuclear reactions, and is responsible for the X–ray emission.[1,2]

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One explanation of the origin of the quiescent X–ray emission is the deep crustal heating. The NS accretes hydrogen and helium-rich material from its companion at rates $\sim 10^{15}$–$10^{18}\,\mathrm{g\,s^{-1}}$. This matter undergoes thermonuclear fusion within hours to days of reaching the NS surface, releasing $\approx 5\,\mathrm{MeV}$ nucleon^{-1} for solar abundances. The nuclear burning is thermally unstable on weakly magnetized NS ($B \ll 10^{11}$ G) accreting at $\dot{M} < 10^{18}\,\mathrm{g\,s^{-1}}$ and produces energetic (10^{39} ergs) type I X–ray bursts when $\dot{M} < 10^{17}\,\mathrm{g\,s^{-1}}$. For steady state models at higher accretion rates, the flux is dominated by the nuclear energy release from the conversion of hydrogen and helium to heavy elements.[3] There is also energy generated in the crust due to electron captures, neutron emission, and pycnonuclear reactions.[4] In this way, the NS crust is heated up beyond the thermal equilibrium with the interior and, once accretion falls to quiescent levels, it cools by thermal radiation (mainly in the X–ray band as the typical temperatures) as the outer layers return to equilibrium.

There are a few long-duration transient sources with outburst periods $t_o \sim 10\,\mathrm{yr}$ (e.g. KS 1731-260 and MXB 1659-29) that have been accreting in the last decade and have recently been detected in quiescence.[1,2] Since the duration of the outbursts is of the same order as the thermal diffusion timescale of the crust, at the end of such long accretion period the NS crust is heated up. The origin of the quiescent luminosity is the release of heat stored in the NS crust during the most recent outburst on a timescale $\sim$1–10 yr.[5] Comparison of observational data with crustal cooling models allows to investigate crust properties and, eventually, ultradense matter processes with influence on the cooling curves. Previous simulations of the relaxation after bursts[6,7] suggested a rather high thermal conductivity in the outer crust (which requires a low impurity content) and were compatible with models without enhanced neutrino emissivity in the core.

2. Neutron Star Baseline Model

2.1. *Composition and transport properties*

The outer crust of a NS consists of a strongly-coupled plasma of nuclei and electrons while the inner crust is a lattice of neutron-rich nuclei in equilibrium with a free neutron gas. The core is made of nuclear uniform matter described by a Skyrme-type equation of state (EoS).[8] The crust composition of an accreting NS crust differs significantly from that of an isolated NS because it has accreted enough matter to entirely replace the whole crust. According to theoretical models, the composition changes abruptly with depth, at locations corresponding to thresholds for electron captures or pycnonuclear reactions[4,9] (see Fig. 1). The stationary temperature profile of the inner crust is determined by the thermal conductivity, which is dominated by electron–phonon scattering processes in the outer crust and by electron-impurity scattering in the inner crust. The thermal relaxation time is controlled by both, the thermal conductivity and the specific heat. The ion lattice contribution to the specific heat dominates at low density while free neutrons and

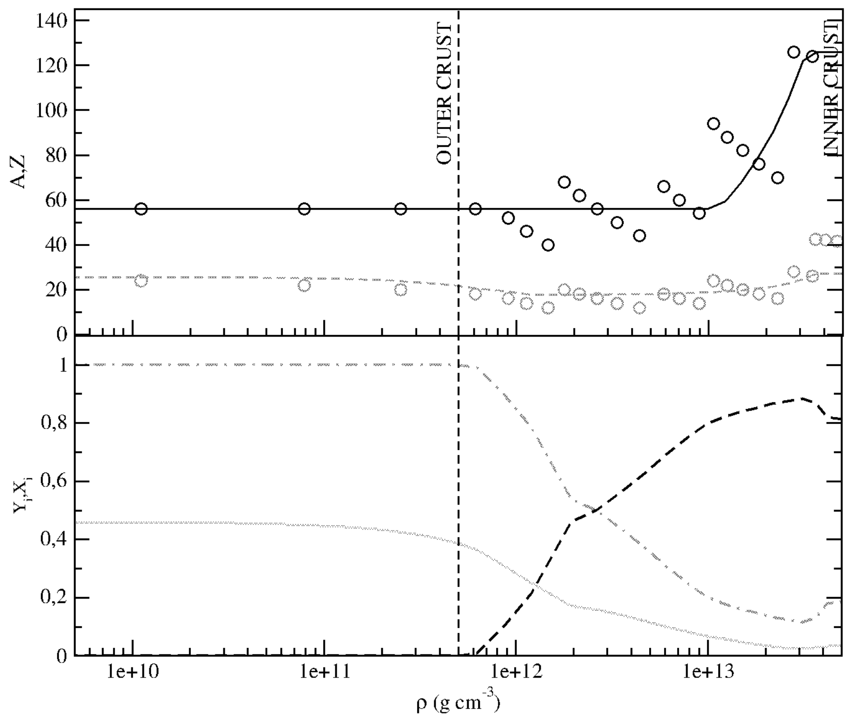

Fig. 1. NS Composition. Upper panel: Interpolation of nuclear charge Z (solid line) and nuclear mass A (dashed line) versus density. Open dots are data taken from Ref. 4. Lower panel: Number of particles per baryon versus density; y_e (solid line), y_n (dashed line), and x_h (dashed-dotted lines).

electrons contribute to the specific heat at high density. In the inner crust, the specific heat of free neutrons is suppressed due to the $^1S_0$ pairing taken from Ref. 10.

We include all relevant neutrino emission processes in the crust.[11] At high temperatures ($T \simeq 10^9\,\mathrm{K}$), the dominant process is plasmon decay. At intermediate values ($T \simeq 5 \times 10^8\,\mathrm{K}$), plasmon decay is only dominant in the outer crust, while electron–nuclei *bremsstrahlung* becomes more efficient in a large part of the crust volume.

2.2. *Nuclear heating*

We consider the heat generation within the NS crust by electron captures, neutron emission and absorption from nuclei, and pycnonuclear reactions at densities $>10^{12}\,\mathrm{g\,cm^{-3}}$[4] (Fig. 2, left panel). The total crust heating rate per accreted nucleon, $Q_{\mathrm{tot}} = 1.9\,\mathrm{MeV/nucleon}$, is quite insensitive to the depth at which pycnonuclear fusion occurs.[4]

3. Time-Dependent Heating and Neutrino Cooling

The NS thermal evolution can be described by the energy balance equation:

$$c_v \frac{\partial T}{\partial t} = -\nabla \cdot F + Q + \epsilon, \tag{1}$$

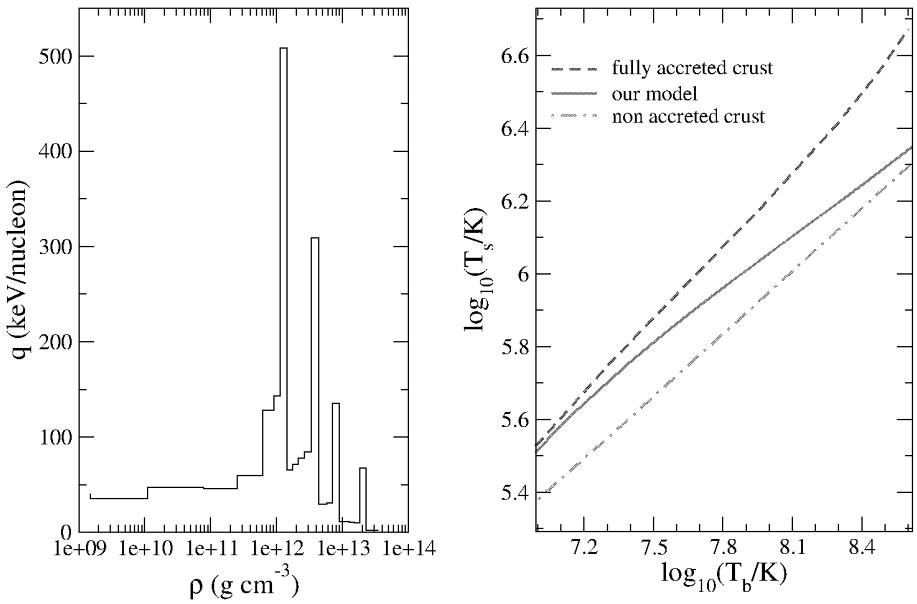

Fig. 2. Left panel: Distribution of heat sources in the crust. Right panel: Relation T_b–T_s for the accreted envelope.

where F is the heat flux, c_v is the specific heat per unit volume, Q considers local energy gains by accretion and ϵ denotes energy losses by neutrino emission.

We assume a constant core temperature, T_c, which we fit to reproduce the observed late time flux, after thermal relaxation of the crust to an isothermal state in equilibrium with the core. We fix the temperature at the base of the envelope, T_b, at a density of $\rho_b = 5 \times 10^8\,\mathrm{g\,cm^{-3}}$. This is the density at which superburst ignition occurs and demarcates the bottom of the region with light element unstable reactions;[7] we use this value as the outer point in the numerical grid. Finally, we use a relation between the surface temperature, T_s, and T_b by integrating the steady-state thermal structure of the envelope without heating sources (Fig. 2, right panel). Its composition is fixed to be ^4H_e down to a density of $2.6 \times 10^6\,\mathrm{g\,cm^{-3}}$, with a layer of pure $^{56}F_e$ down to a density $\rho = 5 \times 10^8\,\mathrm{g\,cm^{-3}}$.

4. Discussion of Results

We calculate cooling curves and compare them with recent observational data[1,2] of two sources MXB 1659-29 and KS 1731-260 (Fig. 3). The initial model for our simulations of the cooling stage consists of a thermally relaxed model that simulates the accretion phase. This is done by switching-on deep crustal heating produced by a constant mass accretion rate $\dot{M}$ and fixing the surface temperature T_s to a constant value, controlled by light element burning. The duration of the accretion period is 12 yrs for KS 1731-260, and 2.5 yrs for MXB 1659-29. In that period, a certain amount of heat, $Q_{\rm tot}$, is deposited into the crust which becomes hot and goes out of the thermal balance with the core. After that, we switch-off accretion heating, free T_s, and the crust cools down. A part of $Q_{\rm tot}$ diffuses out to the surface

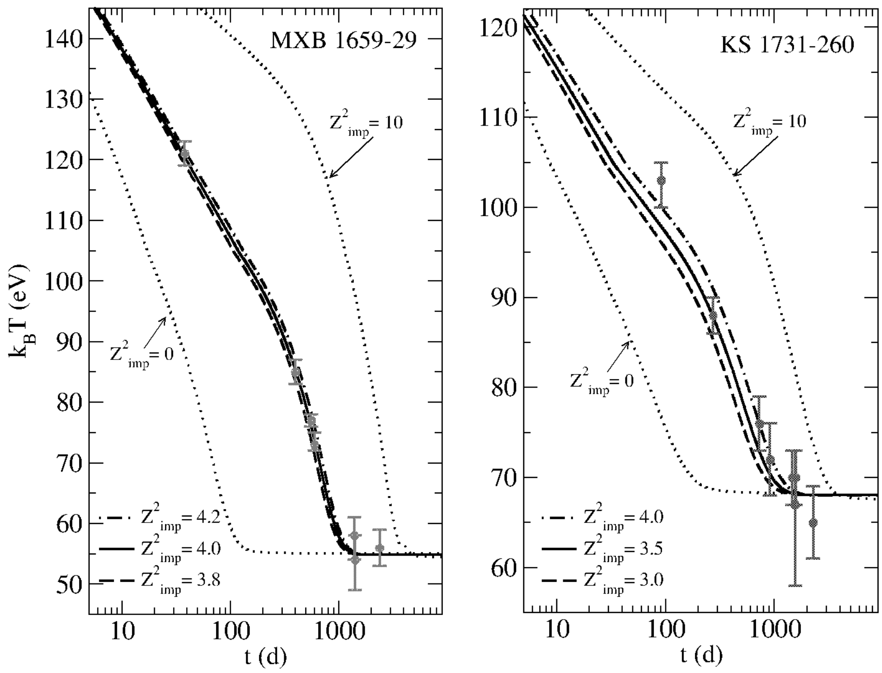

Fig. 3. Comparison between observations of MXB 1659-29 (left panel) and KS 1731-260 (right panel) with cooling curves varying $Z_{\rm imp}$ and fixing T_c, T_c and $\dot{M}$ to fiducial values (see text).

and the rest is carried by thermal conduction into the core, where it is lost by neutrino emission without affecting the surface temperature. The core temperature stays almost unchanged because of the high core thermal conductivity and heat capacity.

For a given hydrostatic structure, the parameters that affect light curves are T_c, T_b, $\dot{M}$ and the thermal conductivity of the crust, which major uncertainty stems from the impurity parameter of the ion lattice defined as

$$Z^2_{\rm imp} = n^{-1}_{\rm ion} \sum_i n_i (Z_i - \langle Z \rangle)^2, \tag{2}$$

where $n_{\rm ion}$ is the ion number density, and n_i and Z_i are respectively the corresponding number density and nuclear charge for individual species labeled by i.

In Fig. 3 we compare cooling curves with observations of both sources. The optimal fit parameters for MXB 1659-29 are $T_c = 2.6 \times 10^7$ K, $T_b = 3.8 \times 10^8$ K, according to previous estimates.[2] For KS 1731-260, we obtain $T_c = 4.3 \times 10^7$ K, $T_b = 2.5 \times 10^8$ K. In both cases $\dot{M} = 10^{17}\,{\rm g\,s^{-1}}$.

Despite the differences in the numerical approach with respect to Refs. 6 and 7, the fact the we use more elaborated thermal conductivities particularly for the electron–phonon processes, and the superfluid neutron component in the inner crust, our results show a good agreement with previous works. We also find that the light curve is a broken power-law, and our fits give similar parameters. Once the system has returned to thermal equilibrium, the luminosity at late times is set by T_c, while the slope of the early part of the light curve depends strongly on $Z_{\rm imp}$ and on T_b. Our results confirm that low values of $Z_{\rm imp} \sim 2$ fit the observational data and the crust has rather high thermal conductivity. The effect of increasing $Z_{\rm imp}$ is to suppress electron conduction and delay the cooling (Fig. 3, both panels). This can be understood in terms of the temperature profile after a burst: the conductivity in the inner crust is lower, which results in a large temperature gradient. Therefore, the hotter outer crust keeps the star surface warmer and the cooling curve falls down more slowly. Early observations taken after a long accretion period would be the ideal scenario for mapping out nuclear heating in the outer crust.

Since our main purpose has been to facilitate comparison and to independently verify previous results, in this paper we have analyzed the same models of Ref. 7, and we have followed them in the treatment of the outer boundary condition during the accretion stage, by leaving T_b as a free parameter. In principle, one could solve stationary envelope models including heating by nuclear burning of light elements, and determine T_b for a fixed accretion rate and composition of the accreting material. This will remove one of the parameters by relating T_b and $\dot{M}$ on physical grounds. Another limitation of our model is that a uniform heat distribution in the envelope is assumed; a more realistic description might include a density-dependent heat deposition. This work is in progress and a more detailed study will be presented elsewhere (Turlione *et al.*, 2010, in preparation).

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