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Inferring neutron stars crust properties from quiescent thermal emission

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Abstract The observation of thermal emission from isolated neutron stars and the modeling of the corresponding cooling curves has been very useful to get information on the properties of matter at very high densities. More recently, the detection of quiescent thermal emission from neutron stars in low mass X-ray binary systems after active periods opened a new window to the physics of matter at lower densities. Here we analyze a few sources that have been recently monitored and we show how the models can be used to establish constraints on the crust composition and their transport properties, depending on the astrophysical scenarios assumed.

1 Introduction

Neutron stars in binary systems with a low-mass companion star (LMXBs) are most of the time in a quiescent state where almost no accretion occurs and a relative low X-ray luminosity ($< 10^{34}\,\mathrm{erg\,s^{-1}}$) is observed. But, occasionally, an accretion episode occurs leading to an increase of the observed luminosity of 2-5 orders of magnitude. The accreted material, rich in light elements (H, He), is transferred at rates comparable to Eddington's accretion rates (typically 1-100%). Once that material reaches the neutron star it undergoes thermal fusion releasing an energy of a few MeV per accreted nucleon, what produces energetic type I X-rays in weekly magnetized systems [1]. When the active phase ends, the X-ray emission decreases dramatically returning to the quiescent levels it had before outbursts. In quasi-persistent sources (a few cases detected in the last 15 yrs) the accretion periods last for a relatively long time: years or decades followed by a reduction in the X-ray luminosity that lasts for about 10^3 days after the end of the outburst. These sources are MXB 1659−29 [2], KS 1731−260 [3], EXO 0748−676 [4], XTE J1701−462 [5], and IGR J17480−2446 [6].

2 Deep crustal cooling and beyond

The quiescent X-ray emission in quasi-persistent sources is thought to be originated in the thermal relaxation of the neutron star crust because the accretion phase is about as long as the crustal diffusion timescale ($\sim$ yr). Numerical simulations of the crust thermal evolution have been performed recently in [7] and previously in [8]. Before the active phase the neutron star is supposed to be old enough to have an isothermal interior and its surface temperature reflects the core temperature. During the active phase the crust is heated up beyond thermal equilibrium by the accretion of matter that compresses the crust and triggers nuclear reactions. Once accretion stops the outer layers return to an equilibrium with the interior, a process in which the neutron star cools down by thermal radiation from the surface as X-rays, by heat conduction toward the core and consequent neutrino emission from the core [9]. We investigated these processes performing detailed numerical simulations of the heat flow inside a realistic neutron star crust. In the Fig. 2 we show the evolution of the initial thermal profile used to study the cooling of MXB 1659−29, one of the sources considered as *crustal coolers* in [7].

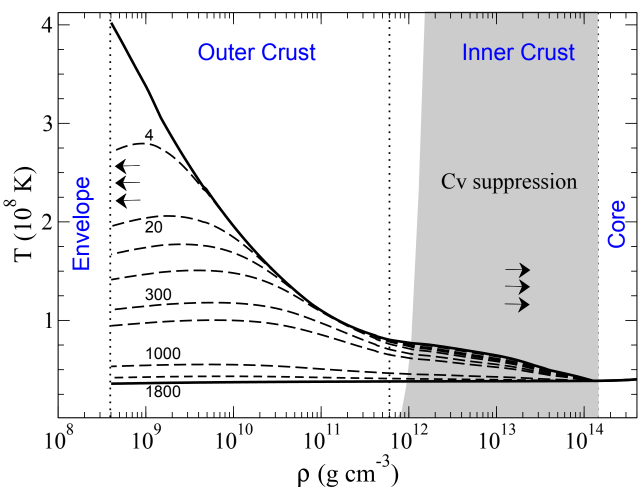

Figure 1: Evolution of the initial thermal profile for MXB 1659−29. The solid line indicates the temperature across the neutron star crust at $t = 0$; the dashed-lines show the further evolution of the temperature at $t = 4, 20, 300, 1000$ days. At 1800 days the equilibrium temperature is reached in the whole crust (solid line at the bottom). The arrows indicate the heat flux direction inside the crust [11].

As a result of this long-term accretion phase, the cooling is modified not only by the energy released in the envelope (at densities 10^4–$10^7\,\mathrm{g\,cm^{-3}}$) by thermonuclear reactions, but also by the energy generated in the inner crust (at 10^{11}–$10^{13}\,\mathrm{g\,cm^{-3}}$)

by electron captures, neutron emission, and density-driven nuclear fusion reactions (pycnonuclear reactions). The so-called *deep crustal heating* controls the evolution in the quiescence phase and the comparison of observational data with theoretical models allows the investigation of crust properties and ultra-dense matter processes.

Simulations of the crust relaxation after outbursts for KS 1731−260 and MXB 1659−29 suggested a rather high thermal conductivity in the outer crust [8] and we found that the evolution of MXB 1659−29, KS 1731−260 and EXO 0748−676 can be well described within a deep crustal cooling scenario (Fig. 2). Nevertheless, some issues

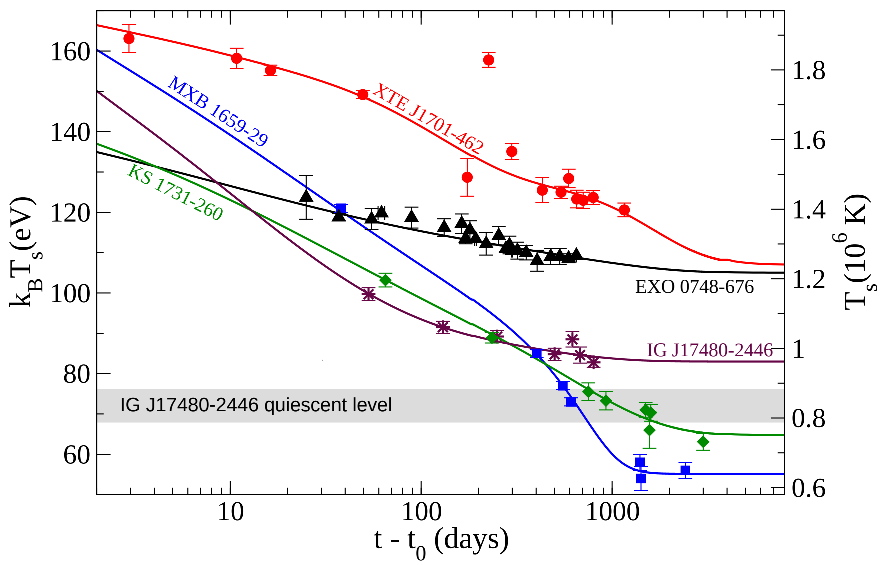

Figure 2: Cooling curves obtained from simulations of the crust thermal evolution (taken from [7]). The fits correspond to crustal cooling for MXB 1659−29 and EXO 0748−676, and with addition of: a small energy gap for neutron superfluidity for KS 1731−260, shallow heat sources in the outer crust for XTE J1701−462 and a high temperature for the neutron star core for IGR J17480−2446.

remain open in the search of a model that can explain all the observations consistently, specially for the peculiar emission of XTE J1701−462 and IGR J17480−2446 [7, 10]. We proposed different astrophysical scenarios *beyond crustal cooling* to explain the variability in XTE J1701−462 like residual accretion during quiescence, additional heat sources in the outer crust, and/or thermal isolation of the inner crust due to a buried magnetic field. We also explained the recent reported temperature of IGR J17480−2446 with an additional heat deposition in the outer crust from shallow sources (Fig. 2). Future monitoring of these sources will determine which scenario is favored, or at least if some of them can be ruled out.

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