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Heat diffusion in outer crust and X-ray superbursts of accreting neutron stars

A.D. Kaminker[1], D.G. Yakovlev[1], A.Y. Potekhin[1], P. Haensel[2]
kam.astro@mail.ioffe,
WWW home page: http://www.ioffe.ru/DTA/kam/kam.html

[1] *Ioffe Institute, Politekhnicheskaya 26, St Petersburg 194021, Russia,*
[2] *Copernicus Astronomical Center, Bartycka 18, 00-716 Warsaw, Poland*

A simple model is presented of heat diffusion after a superburst in deep layers of the outer crust of an accreting neutron star ($10^7 \lesssim \rho \lesssim 4 \times 10^{11}$ g cm^{-3}). Since the warm outer crust ($T \sim 10^8 - 10^9$ K) has large heat capacity and acts as a heat reservoir, it is able to keep the outburst energy for months. The basic features of thermal afterburst evolution are outlined. They can be useful for interpreting observations of superbursts in low-mass X-ray binaries.

Keywords: conduction – dense matter – stars: neutron – X-rays: bursts

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Superbursts constitute a special class of X-ray bursts (e.g., [1, 2]) demonstrated by some accreting neutron stars (NSs). These bursts are rare events. They differ from standard type Ia X-ray bursts mainly because they are more powerful and longer. Standard bursts are interpreted as explosive nuclear burning of accreted hydrogen and/or helim just under the surface of NSs, at densities $\rho \lesssim 10^5$ g cm^{-3}. In contrast, superbursts are thought to be powered by explosive burning of carbon (^{12}C) that is produced during nuclear evolution of accreted matter. Carbon can survive in NSs to much higher densities $\rho \sim (10^7 - 10^{10})$ g cm^{-3}. According to the theory, a layer of carbon accumulated to the ignition depth $\rho_{\rm ign}$ burns out in few seconds. Some fraction of the generated heat is carried away to the surface producing an observable event. Another fraction is thermally conducted inside the star, while the rest is carried away by neutrino emission from a hot burning shell.

Here we focus on heat diffusion in the NS crust. The problem has been extensively studied, mainly by direct modeling (e.g. [3, 4, 5, 6, 7, 8] and references therein). We combine modeling and semi-analytic consideration and outline most reliable results. More detailed discussion is given in [9] (hereafter P1).

A short explosive carbon burning produces heavy (iron-like) elements, huge heat release and temperature rise on spot; heat has no time to spread away. After that one can distinguish three main superburst stages.

Stage I is characterized by an efficient heat transport from the ignited layer to the surface by heat diffusion and/or convection, accompanied by neutrino cooling. This stage ends with the appearance of a quasi-stationary heat outflow to the surface from top of the ignited layer.

Stage II is accompanied by the strongest energy outflow from the surface; the lightcure $L(t)$ reaches maximum and starts to fade. The temperature profile within the heated layer gradually quasi-equilibrates, starting from top. Then the quasi-equilibration moves inside. Stage II ends when the equilibration reaches the boton of the ignited layer, $\rho \sim \rho_{\rm ign}$. By that time the layer is cooler and the neutrino cooling stops. Since the heat capacity of deep outer crust is large, the thermal wave moves inside the star much slower than outside.

At the final stage III the lightcurve fades, the ignited zone becomes almost isothermal, but the heat continues to diffuse inside the star. This diffusion becomes the main mechanism which regulates temperature drop in the upper layers and at the surface. The fading of $L(t)$ imprints the information on properties of NS matter.

Superbursts can be studied with full thermal evolution codes (e.g. [7]), which can simulate (in General Relativity) creation of the carbon layer from accreted H/He matter, subsequent explosion and evolution. However, if one wants to focus on diffusion of heat after the explosion, one can start with the burst of an assumed carbon layer and follow heat propagation within the outer NS crust (a thin layer under the surface, e.g. [10]). The space-time is locally flat there and heat conduction is described by the equation $C\partial T/\partial t - \partial(\kappa \partial T \partial z)/\partial z = Q$, where T is the non-redshifted local temperature, z is the proper depth from the surface, C is the heat capacity per unit volume, κ is the thermal conductivity, and Q is the heat generation rate per unit volume. At densities 10^7 g cm^{-3} $\lesssim \rho \lesssim 10^{11}$ g cm^{-3} and temperatures 10^8 K $\lesssim T \lesssim 3 \times 10^9$ K, important for superbursts, it is a good approximation to set $\rho \propto z^3$, $C \propto z^3$ and $\kappa \propto z^2$. Then the equation becomes linear in T, and its Green's function in the free heat propagation regime can be found in the analytic form. This gives an easily programmable (toy) solution for the temperature T as a function of z (or ρ) and t for any source function Q (see P1).

Fig. 1 shows semi-analytic toy (a) and exact (b) solutions for a star of mass $1.4\,M_\odot$ and radius $R = 12$ km. The exact solution has been obtained using the numerical code presented by [11] (see details in P1). Shown are snapshots of $T(\rho, t)$ at certain moments of non-redshifted time t. The exploded carbon layer extends to $\rho_{\rm ign} = 10^8$ g cm^{-3}, the burst duration is 100 s. The fuel calorimetry (5 keV per nucleon) is intentionally taken small (for real superbursts) to avoid heating of the matter to $T \gtrsim 3 \times 10^9$ K, which would trigger strong neutrino emission disregarded in the toy model. The total energy release for the burst in Fig. 1 is $\approx 10^{40}$ erg.

The temperature profiles in panels (a) and (b) qualitatively agree. Some disagreement occurs because the toy model uses simplified C and κ. Note that this model cannot be directly extended to the surface, which complicates calculation of the toy lightcurves.

The inset on panel (b) shows the computed (non-redshifted) lightcurve $L(t)$. In our case, only $\approx 1/4$ of the released heat escapes from the surface. Stage I lasts for about 10 min, stage II for ~ 10 h, and the burst fades in a few weeks. The inward thermal wave needs months to reach the bottom of the outer crust.

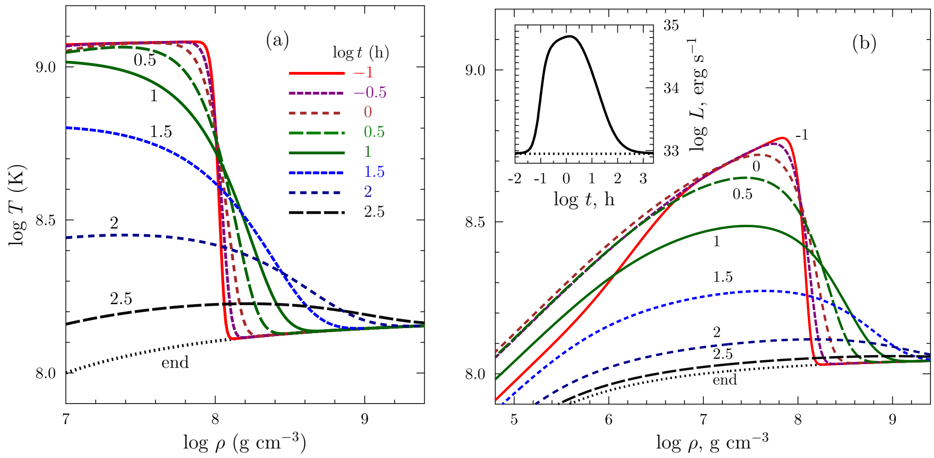

Figure 1: Snapshots of internal temperature $T(\rho)$ versus density after carbon explosion at $\rho \leq 10^8\,\mathrm{g\,cm^{-3}}$ in different moments of time (labeled by $\log t$ [h]). Calculations are performed with the semi-analytic toy model (a) and a computer code (b). The inset in panel (b) is shows the lightcurve computed by the code. The dotted lines (marked 'end') refer to a quiet NS. After Figs. 6 and 7 in P1. See text for details.

The onset of phase III is marked by the beginning of power-law-like tail of the lightcurve at time $t = t_{\rm tr}$, which can be inferred from observations of lightcurves. This time is identified as the heat propagation time from the bottom of the ignited layer ($\rho = \rho_{\rm ign}$) at some (neatly uniform) temperature $T \approx T_{\rm tr}$. For the star with $M = 1.4\,M_\odot$ and $R = 12$ km, the dependence of $t_{\rm tr}$ on $T_{\rm tr}$ and $\rho_{\rm ign}$ has been approximated by Eq. (18) in P1. The redshifted time $t^{\rm S}_{\rm tr}$ for arbitrary M and R is given by Eq. (19) in P1. For instance, for the outburst of KS 1731–269 [12] one has $t^{\rm S}_{\rm tr} \approx 10$ h. If $M = 1.4\,M_\odot$ and $R = 10$ km for $\log T_{\rm tr}[\mathrm{K}] \approx 9 - 9.3$, we can obtain $\log \rho_{\rm ign}[\mathrm{g\ cm^{-3}}] \approx 8.7$, which agrees with calculations by [4]. Taking $R = 12$ km for the same M and $T_{\rm tr}$, we have noticeably smaller $\log \rho_{\rm ign}[\mathrm{g\ cm^{-3}}] \approx 8.2$. Therefore, the ignition depth and other burst parameters do depend on M and R.

The thermal evolution at stage III is accompanied by a power-law fading of the ignition curve and slow propagation of the inward thermal wave in the outer NS crust. The heat capacity of this crust is sufficient to absorb $\sim (10^{43} - 10^{44})$ erg. As long as the thermal wave moves in, the surface stays thermally decoupled from the NS inteior.

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