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Deep Crustal Heating in Accreted Neutron Star Crusts Using the Brussels-Montreal HFB-27* Nuclear Mass Model

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Abstract. X-ray observations of accreting neutron stars in low-mass X-ray binaries have recently proved to be very useful for probing neutron-star interiors. We have recently studied the release of heat due to nonequilibrium nuclear processes in the crust of an accreting neutron star using the microscopic Brussels-Montreal HFB-27* nuclear mass model, based on the self consistent Hartree-Fock-Bogoliubov method. This model was fitted to essentially all atomic masses with a model root mean square deviation of 0.5 MeV. Moreover, the underlying functional was adjusted to realistic equations of state of neutron matter and was constrained to reproduce various properties of nuclear matter.

1 Introduction

In a low-mass X-ray binary, a neutron star (NS) accretes matter from a companion star whose mass is significantly less than that of our Sun (see, *e.g.* Ref. [1] for a review). Matter is transferred from the companion towards the NS surface through the inner Lagrangian point, via an accretion disk. The accretion process can last for billions of years. A hydrogen atom falling on a NS surface from infinity releases ~ 200 MeV of gravitational binding energy. Most of this energy is radiated in X-rays, with a total luminosity $L_{\rm X} \sim 10^{36}$ erg s^{-1}. Accreted matter is usually hydrogen rich and forms the outer envelope of the NS. Stable hydrogen burning releases ~ 5 MeV/nucleon. The helium ashes ignite under specific conditions of density and temperature (typically at density $\rho \sim 10^7$ g cm^{-3}). For some range of accretion rate, helium burning is unstable: within seconds all the envelope is converted into nuclides of the iron group and beyond. These thermonuclear flashes are observed as (type I) X-ray bursts, with luminosity up to about 10^{38} erg s^{-1} ($\approx$ Eddington limit for NSs), and with a typical decay lasting a few tens of seconds. The X-ray bursts are quasiperiodic, with typical recurrence time of about hours to days. Many bursters are of transient character, and form a group of soft X-ray transients (SXTs), with typical active periods of days to weeks, separated by periods of quiescence that can last several months to years. During quiescent periods, there is very little or no accretion, while during much shorter periods of activity there is an abundant accretion, probably due to disc flow instability. Some SXTs, with active periods of years separated by decades of quiescence, are called persistent SXTs. In 2000, a special type of X-ray *superbursts* was discovered. Superbursts last for a few to twelve hours, with recurrence times of several years. The total energy radiated in a superburst is $\sim 10^{42}$ erg and they are explained by the unstable burning of carbon in deep layers of the outer crust.

Since both X-ray bursts and superbursts take place above the NS crust, and are sensitive to the crust structure and to its physical conditions, the observation of these phenomena can give valuable information on the NS crust properties. The thermal relaxations of a few SXTs have been recently monitored, and suggest the existence of shallow heat sources in the crust (see, *e.g.* Refs. [2, 3]). We have studied the release of heat due to nonequilibrium nuclear processes in the crust of an accreting NS using the Brussels-Montreal HFB-27* nuclear mass model [4].

2 Deep Crustal Heating

The composition of the crust of an accreting NS in a low-mass X-ray binary can be very different from that of a nonaccreting NS depending on the duration of accretion. In particular, the original outer crust, containing a mass $\sim 10^{-5}\,M_{\odot}$ (with $M_{\odot}$ the mass of the Sun), is replaced by the accreted crust in about 10^4 years for an accretion rate $10^{-9}\ M_{\odot}$ per year. Therefore, to replace the whole crust (with a mass of $\sim 10^{-2}\,M_{\odot}$) by accreted matter requires 10^7 years. At the end, the entire "old crust" is pushed down, and is molten into the liquid core. During accretion, the crust is driven out of its thermal equilibrium, and thus constitutes a reservoir of energy, which can then be released during the stellar evolution [5].

X-ray burst ashes, produced at densities $\rho \lesssim 10^7$ g cm^{-3}, sink deeper and deeper under the weight of accreted matter. At densities $\rho > 10^8$ g cm^{-3}, matter is strongly degenerate, and is "relatively cold" ($T \lesssim 10^8$ K), so that thermonuclear processes are strongly suppressed. However, nuclei with atomic number Z and mass number A may capture electrons with the emission of neutrinos in two steps:

$$(A, Z) + e^- \longrightarrow (A, Z-1) + \nu_e\,, \tag{1}$$

$$(A, Z-1) + e^- \longrightarrow (A, Z-2) + \nu_e + Q_j\,. \tag{2}$$

The first capture proceeds in *quasi-equilibrium*, with negligible energy release. The daughter nucleus is generally highly unstable, and captures a second electron *off equilibrium* with an energy release Q_j. Beyond the neutron-drip point (at densities above a few times 10^{11} g cm^{-3}), electron captures are accompanied by neutron emissions. At high enough densities $\rho \gtrsim 10^{12}$ g cm^{-3}, nuclei may also undergo pycnonuclear fusion reactions [5].

This scenario of deep crustal heating is supported by observations of SXTs in quiescence. However, the recent monitoring of a few SXTs suggest the existence of an additional shallow heat source in the outer crust.

3 Model of Accreted Neutron-Star Crusts

Under the condition generally prevailing in accreting NS crusts, $\rho \gtrsim 10^7$ g cm^{-3} and $T < 10^8$ K, the thermal contributions to the thermodynamic potentials can be neglected, and we shall therefore consider $T = 0$. The outer crust is supposed to be made of fully ionised atoms arranged in a body-centered cubic lattice, neutralised by a degenerate electron gas. For simplicity, any crustal layer is assumed to contain only one type of nuclides with atomic number Z and mass number A.

The pressure P_β at the onset of electron captures by nuclei is determined by the condition $g(A, Z, P_\beta) = g(A, Z-1, P_\beta)$, where g denotes the Gibbs free energy per nucleon. A second electron capture will occur provided $g(A, Z-2, P_\beta) < g(A, Z, P_\beta)$. The heat released per one accreted nucleon is approximately given by [5]

$$\frac{Q_{\rm cell}}{A} \approx g(A, Z, P_\beta) - g(A, Z-2, P_\beta)\,. \tag{3}$$

Considering ultrarelativistic electrons, the Gibbs free energy per nucleon is approximately given by

$$g \approx \frac{M(A,Z)c^2}{A} + \frac{Z}{A}\left[1 + \frac{4C\alpha}{(81\pi^2)^{1/3}} Z^{2/3}\right]^{3/4} (12\pi^2\hbar^3 c^3 P)^{1/4}\,, \tag{4}$$

where $M(A, Z)$ is the nuclear mass (including the rest mass of A nucleons and Z electrons), $C \approx -1.444$ [6] is the lattice constant, $\alpha = e^2/\hbar c$, and e is the elementary electric charge. The average baryon density for the onset of electron captures is approximately given by [7]

$$\bar{n}_\beta(A, Z) \approx \frac{A}{Z}\frac{\mu_e^\beta(A,Z)^3}{3\pi^2(\hbar c)^3}\left[1 + \frac{C\alpha}{(3\pi^2)^{1/3}}\left(Z^{5/3} - (Z-1)^{5/3} + \frac{Z^{2/3}}{3}\right)\right]^{-3}, \tag{5}$$

where

$$\mu_e^\beta(A, Z) \equiv M(A, Z-1)c^2 - M(A,Z)c^2 + m_e c^2\,, \tag{6}$$

m_e being the electron mass. The corresponding pressure is approximately given by

$$\begin{aligned} P_\beta(A,Z) &\approx \frac{\mu_e^\beta(A,Z)^4}{12\pi^2(\hbar c)^3}\left[1 + \frac{4C\alpha Z^{2/3}}{(81\pi^2)^{1/3}}\right] \\ &\times \left[1 + \frac{C\alpha}{(3\pi^2)^{1/3}}\left(Z^{5/3} - (Z-1)^{5/3} + \frac{Z^{2/3}}{3}\right)\right]^{-4}. \end{aligned} \tag{7}$$

As nuclei from X-ray burst ashes sink into the crust, Z decreases due to electron captures whereas A remains unchanged. We assume here that pycnonuclear reactions only occur in the inner crust, where nuclei are immersed in a neutron liquid. At some point, nuclei will be so neutron rich that they will capture one electron and emit ΔN neutrons of mass m_n. Given the initial composition (A, Z) of the X-ray burst ashes, the neutron drip will occur for the nucleus with the highest proton number Z (lying below the initial atomic number) for which the ΔN-neutron separation energy, defined as

$$S_{\Delta Nn}(A, Z-1) \equiv M(A-\Delta N, Z-1) - M(A, Z-1) + \Delta N m_n\,, \quad (8)$$

is negative [7]. The average baryon density and pressure for the onset of neutron drip is approximately given by (Z_d being the atomic number of the dripping nucleus)

$$\bar{n}_{\text{drip-acc}} \approx \frac{A}{Z_d}\frac{(\mu_e^{\text{drip-acc}})^3}{3\pi^2(\hbar c)^3}\left[1+\frac{C\alpha}{(3\pi^2)^{1/3}}\left(Z_d^{5/3}-(Z_d-1)^{5/3}+\frac{Z_d^{2/3}}{3}\right)\right]^{-3}, \quad (9)$$

$$P_{\text{drip-acc}} \approx \frac{(\mu_e^{\text{drip-acc}})^4}{12\pi^2(\hbar c)^3}\left[1+\frac{4C\alpha Z_d^{2/3}}{(81\pi^2)^{1/3}}\right] \times \left[1+\frac{C\alpha}{(3\pi^2)^{1/3}}\left(Z_d^{5/3}-(Z_d-1)^{5/3}+\frac{Z_d^{2/3}}{3}\right)\right]^{-4}, \quad (10)$$

where

$$\mu_e^{\text{drip-acc}} = M(A-\Delta N, Z_d-1)c^2 - M(A, Z_d)c^2 + \Delta N m_n c^2 + m_e c^2\,. \quad (11)$$

4 Results and Discussions

The only microscopic inputs to model the outer crust of an accreted NS are the nuclear masses $M(A, Z)$, which were obtained from the available experimental atomic masses [8] after subtracting out the binding energy of atomic electrons [9]. For the masses that have not yet been measured, we used the Brussels-Montreal HFB-27* microscopic atomic mass model [4]. This model fits the 2353 measured masses of nuclei with N and $Z \geq 8$ appearing in the 2012 Atomic Mass Evaluation [8], with a model standard deviation as low as $\sigma_{\text{mod}} = 0.500$ MeV. Masses were obtained from self-consistent Hartree-Fock-Bogoliubov calculations (see *e.g.* Ref. [10] for a short review). At the same time, the nuclear-matter properties predicted by the underlying functional are consistent with both experiments and calculations based on realistic nucleon-nucleon potentials. The HFB-27* model and the underlying functional have been recently applied to compute the properties of nonaccreting NS crusts [11]. As in Ref. [5], we assumed that the ashes of the X-ray bursts consist of pure ^{56}Fe.

Table 1. Nonequilibrium processes in the outer crust of an accreting neutron star considering X-ray bursts ashes made of ^{56}Fe. For each process, ρ denotes the average mass-energy density at which it occurs, and $Q_{\rm cell}/A$ is the heat released per one accreted nucleon (experimental values are indicated in boldface).

	ρ (g cm^{-3})	$Q_{\rm cell}/A$ (MeV)
^{56}Fe $+ 2e^- \rightarrow^{56}$ Cr $+ 2\nu_e$	$\mathbf{1.37 \times 10^9}$	**0.0370**
^{56}Cr $+ 2e^- \rightarrow^{56}$ Ti $+ 2\nu_e$	$\mathbf{1.83 \times 10^{10}}$	**0.0402**
^{56}Ti $+ 2e^- \rightarrow^{56}$ Ca $+ 2\nu_e$	6.12×10^{10}	0.0310
^{56}Ca $+ 2e^- \rightarrow^{56}$ Ar $+ 2\nu_e$	2.36×10^{11}	0.0284

The sequence of electron captures and the associated heat releases are indicated in Table 1. In the shallowest region at density $\rho \lesssim 1.83 \times 10^{10}$ g cm^{-3}, the heat released is completely determined by experimental masses. In deeper layers, the heat released is model dependent. However, the total amount of heat does not significantly differ from that found previously [5].

As shown in Figure 1, the composition of accreted crust deviates significantly from that of nonaccreting (catalysed) crust. Note that in this work we used an updated version of the HFB-27* mass table [12] so that our results for catalysed crust are slightly different from those obtained in Ref. [11].

At density $\rho_{\text{drip-acc}} \simeq 4.65 \times 10^{11}$ g cm^{-3} corresponding to the pressure $P_{\text{drip-acc}} \simeq 9.55 \times 10^{29}$ dyn cm^{-2}, the nucleus ^{56}Ar was found to be unstable against one neutron emission: ^{56}Ar $+ e^- \rightarrow^{55}$ Cl $+ n + \nu_e$. For com-

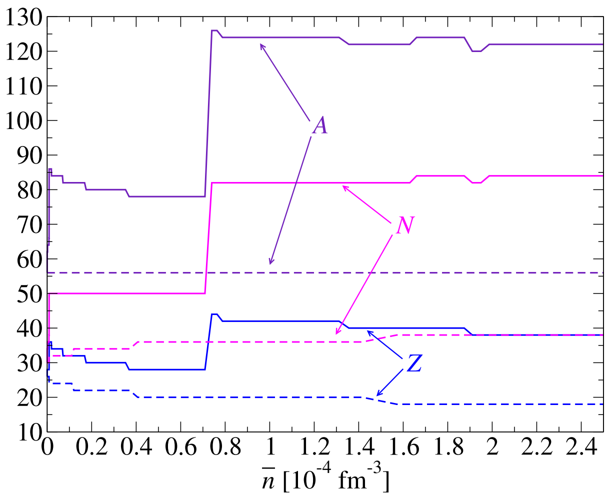

Figure 1. Composition of accreted crust (dashed lines) and catalyzed crust (solid lines): total number of nucleons A, neutrons N, and protons Z as a function of the average baryon number density $\bar{n}$.

parison, the compressible liquid drop model of Ref. [5] predicts $\rho_{\text{drip-acc}} \simeq 5.09 \times 10^{11}$ g cm^{-3}, and pressure $P_{\text{drip-acc}} \simeq 1.07 \times 10^{30}$ dyn cm^{-2} [7].

5 Conclusion

We have calculated the heat released in the outer crust of an accreting NS from nonequilibrium electron capture processes. For this purpose, we have made use of the latest experimental atomic mass data supplemented with the microscopic mass model HFB-27*. Considering X-ray burst ashes made of ^{56}Fe, the total heat released amounts to 0.137 MeV per nucleon. This is found to be of the same order of magnitude as previously calculated by Haensel and Zdunik in Ref. [5]. Therefore, the puzzle of shallow heat sources still remains.

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