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Pycnonuclear burning of ^{34}Ne in accreting neutron stars

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ABSTRACT

We study the pycnonuclear burning of ^{34}Ne in the inner crust of an accreting neutron star. We show that the associated energy production rate can be calculated analytically for any arbitrary temporal variability of the mass accretion rate. We argue that the theoretical time-scale for ^{34}Ne burning is currently very uncertain and ranges from a fraction of a millisecond to a few years. The fastest allowable burning may change the composition of the accreted crust while the slowest burning leads to a time-independent nuclear energy generation rate for a variable accretion. The results are important for constructing self-consistent models of the accreted crust and deep crustal heating in neutron stars which enter soft X-ray transients.

Key words: dense matter – nuclear reactions, nucleosynthesis, abundances – stars: neutron.

1 INTRODUCTION

In this paper, we analyse the hypothesis that quiescent thermal radiation from neutron stars in soft X-ray transients (SXTs) is powered by the deep crustal heating of accreted matter. These SXTs are low-mass X-ray binaries which undergo active states (lasting from days to months) and quiescent periods (from months to decades); see, e.g. Chen, Shrader & Livio (1997). Their activity is most probably regulated by accretion from a disc around the neutron star. In quiescence, when accretion is stopped or greatly suppressed, some SXTs emit thermal radiation which indicates that the neutron stars are warm. A possible explanation of this phenomenon is (Brown, Bildsten & Rutledge 1998) that neutron stars are warmed up by deep crustal heating (Haensel & Zdunik 1990, 2003) produced by nuclear transformations in the accreted matter as it sinks into the crust under the weight of newly accreted matter. These transformations occur in the density range from $\sim 10^8$ to $\sim 10^{13}$ g cm^{-3}. They include electron captures, neutron absorption and emission, converting the nuclei available at the density $\rho \sim 10^8$ g cm^{-3} to neutron-rich light nuclei; these light nuclei then undergo pycnonuclear fusion. Haensel & Zdunik (1990) studied these processes assuming that accreted material was burnt to pure ^{56}Fe matter at $\rho \lesssim 10^8$ g cm^{-3}. Haensel & Zdunik (2003) started from ^{106}Pd (instead of ^{56}Fe) at $\rho \sim 10^8$ g cm^{-3} in response to the results of Schatz et al. (2001) who showed that the rp-process can burn the accreted matter to very heavy nuclei (A = 104–106) at $\rho \lesssim 10^8$ g cm^{-3}. According to Haensel & Zdunik (1990, 2003), the total nuclear energy released in deep crustal heating is 1.1–1.5 MeV per accreted nucleon. The total heating power is $\approx$(6.6–9.0) $\times 10^{33}\, \dot{M}_{-10}$ erg s^{-1}, which is sufficient to explain the observed thermal luminosity of SXTs in quiescence ($\dot{M}_{-10}$ being the mass accretion rate $\dot{M}$ expressed in 10^{-10} M$_\odot$ yr^{-1}). The main energy release occurs in pycnonuclear reactions in the inner crust of the star, at $\rho \gtrsim 10^{12}$ g cm^{-3}, a few hundred metres under the surface.

The idea of deep crustal heating of SXTs is an attractive hypothesis but is not unchallenged. We will discuss the limitations of this hypothesis associated with current uncertainties in pycnonuclear reaction rates.

2 PYCNONUCLEAR BURNING OF ^{34}NE

In the following, we consider the pycnonuclear burning of ^{34}Ne through

$$^{34}\mathrm{Ne} + {}^{34}\mathrm{Ne} \rightarrow {}^{68}\mathrm{Ca} \tag{1}$$

in the model of Haensel & Zdunik (1990). The ^{34}Ne fuel is produced owing to double electron capture by ^{40}Mg ($^{40}\mathrm{Mg} + 2\mathrm{e} \rightarrow {}^{34}\mathrm{Ne} + 6\mathrm{n} + 2\nu_\mathrm{e}$) which occurs at densities exceeding the electron capture threshold, $\rho_1^* = 1.455 \times 10^{12}$ g cm^{-3}. The electron capture is accompanied by a weak first-order phase transition with the density jump from ρ_1^* to $\rho_1 = 1.688 \times 10^{12}$ g cm^{-3}. With further increase of ρ this ^{34}Ne ignites through the pycnonuclear reaction (1) (owing to zero-point vibrations of closest neighbouring nuclei in a cold dense matter; see e.g. Salpeter & Van Horn 1969). The density in the burning layer is so high that the thermal effects can be neglected. The energy generation is substantial, $\approx$0.4 MeV per accreted nucleon. The matter after the jump contains ^{34}Ne, ^{68}Ca, electrons and free neutrons. The fractional number of free neutrons among all nucleons is $X_\mathrm{n} = 0.39$. The next transformation (electron capture by ^{68}Ca) occurs at $\rho = 1.766 \times 10^{12}$ g cm^{-3}, a few metres deeper than the ^{34}Ne production level.

For a typical mass accretion rate $\dot{M} \sim 10^{-10}$ M$_\odot$ yr^{-1} the velocity of matter, inflowing through the ^{34}Ne threshold $\rho = \rho_1$, is $v \sim 10^{-9}$ cm s^{-1}. For any reasonable ^{34}Ne burning times (see below), the burning occurs within a few centimetres after the threshold. In

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the burning layer the density and other parameters of the matter, as well as the accretion velocity v, are almost independent of depth, and the approximation of plane-parallel uniform layer applies. It is sufficient to consider ^{34}Ne burning in a uniform one-dimensional flow with the velocity determined by a generally variable accretion rate, $v(t) \approx \dot{M}(t)/(4\pi\rho_1 r_1^2)$ ($r_1 \approx R$, where R is the radius of the star). In the Lagrangian formalism, the evolution of the ^{34}Ne number density $Y = n_1/\rho$ per gram (determined by its number density n_1 per cm^3) is described by

$$\frac{\mathrm{d}Y}{\mathrm{d}t} = \frac{\partial Y}{\partial t} + v(t)\,\frac{\partial Y}{\partial l} = -\frac{2R}{\rho}, \tag{2}$$

where l is a coordinate inside the star, and R is the reaction rate. The factor of 2 takes into account that two ^{34}Ne nuclei disappear in any reaction event (1). Although neutron stars should be described by general relativity, space–time is locally flat in a local neutron star reference frame on length-scales of interest, and our approximation of flat space–time is justified.

The pycnonuclear fusion rate R for a multicomponent mixture of atomic nuclei has recently been studied by Yakovlev et al. (2006) as a generalization of their results for a one-component plasma of nuclei (Gasques et al. 2005). According to Yakovlev et al. (2006), R is a complicated function of plasma parameters and of the (generally unknown) microstructure of the multicomponent matter. In the following, we assume that ^{34}Ne and ^{68}Ca form a uniform mix. In this case, the rate for the ^{34}Ne+^{34}Ne fusion process can be expressed by $R = K\,x_1^2$, with

$$K = 10^{46}\, C_{\rm pyc}\widetilde{\rho} Z_1^4 \langle A\rangle\, S(E)\,\widetilde{\lambda}^{3-C_{\rm pl}}\, \exp\left(-\frac{C_{\rm exp}}{\sqrt{\widetilde{\lambda}}}\right)\ \ \mathrm{cm^{-3}\ s^{-1}}, \tag{3}$$

$$\widetilde{\lambda} = \alpha_\lambda\,\lambda = \frac{\alpha_\lambda}{A_1 Z_1^{7/3}}\left(\frac{\langle Z\rangle\,\widetilde{\rho}}{\langle A\rangle\, 1.3574\times 10^{11}\ \mathrm{g\ cm^{-3}}}\right)^{1/3}. \tag{4}$$

The subscripts 1 and 2 refer to ^{34}Ne and ^{68}Ca, respectively; $x_1 = n_1/n$, $x_2 = n_2/n$; $n = n_1 + n_2$; $A_1 = 34$, $Z_1 = 10$; $A_2 = 68$, $Z_2 = 20$; $\langle A\rangle = A_1x_1 + A_2x_2$, $\langle Z\rangle = Z_1x_1 + Z_2x_2$; $\widetilde{\rho} = \rho(1 - X_{\rm n})$; the ratio $\langle A\rangle/\langle Z\rangle$ remains constant in the burning layer (and K is constant in our approximation). The astrophysical S-factor for the fusion process (1) has to be taken at the energy of the colliding nuclei $E \approx \hbar\,(4\,\pi e^2 n_{\rm e} Z_1/m_1)^{1/2}$, where m_1 is the mass of the ^{34}Ne nucleus and $n_{\rm e} = \langle Z\rangle\, n$ is the electron number density. In equation (3) the S-factor is expressed in MeV barn, and $\widetilde{\rho}$ in g cm^{-3}. The parameters $C_{\rm exp}, C_{\rm pyc}, C_{\rm pl}$ and α_λ depend on the details of Coulomb tunnelling of reacting nuclei in a dense plasma and have not been calculated precisely. Yakovlev et al. (2006) presented the optimal values of these parameters and their values corresponding to the maximum and minimum theoretical Coulomb-tunnelling rates. We list these parameters in Table 1. Note that Yakovlev et al. (2006) introduced an additional parameter, α_ω, which affects the pycnonuclear reaction rate only slightly and will be neglected here.

We have calculated the S-factor using the techniques outlined by Gasques et al. (2005) and Yakovlev et al. (2006). The S-factor has been fitted in terms of the centre-of-mass energy E (in MeV) by an

Table 1. Coefficients in equation (3).

Model	$C_{\rm exp}$	$C_{\rm pyc}$	$C_{\rm pl}$	α_λ
Optimal	2.638	3.90	1.25	1
Maximum rate	2.450	50	1.25	1.05
Minimum rate	2.650	0.5	1.25	0.95

expression

$$S(E) = \exp\left(a_1 + a_2\,\Delta E + \frac{a_3 + a_4\,\Delta E + a_5\,\Delta E^2}{1 + \mathrm{e}^{-\Delta E}}\right)\ \mathrm{MeV\,b}, \tag{5}$$

for $E \leqslant 20$ MeV, with $\Delta E = E - E_0$; $E_0 = 12.61$ MeV, $a_1 = 118.8$, $a_2 = -1.10$, $a_3 = -4.896$, $a_4 = -1.931$, $a_5 = 0.0581$, and $b = 10^{-24}$ cm^2. Note, that our calculation of $S(E)$ neglects the deformation of atomic nuclei by the pressure of free neutrons in dense matter. It also neglects possible fusion enhancement through an extended neutron halo for such a neutron-rich nucleus as ^{34}Ne. On the other hand, the weak binding energy of this nucleus could significantly reduce the subbarrier fusion cross-section due to the increase of the break-up probability. This introduces large uncertainties into $S(E)$.

Using equation (3), the right-hand side of equation (2) can be written as

$$\frac{2R}{\rho} = \frac{Y^2}{Y_0\tau}, \quad \tau = \frac{n^2}{2Kn_0}, \tag{6}$$

where Y_0 is the value of Y in the non-burnt matter, n_0 is the number density of nuclei in this matter and τ is a characteristic ^{34}Ne burning time. When ^{34}Ne nuclei transform into ^{68}Ca, x_1 decreases from 1 to 0, the total ion number density $n = n(x_1) = n_0/(2 - x_1)$ decreases by a factor of 2, and τ reduces from its initial value $n_0/(2K)$ to its final value $n_0/(8K)$. However, because the theoretical value of τ is highly uncertain (see below) we will treat τ as a constant during the burning and will set $\tau = n_0/(3K)$. This assumption does not violate our main conclusions as was checked by direct numerical solutions of equation (2).

With this assumption, equation (2) is solved analytically,

$$Y(t) = Y_0\,\frac{\tau}{t+\tau}. \tag{7}$$

The Lagrangian coordinate $l(t)$ of an accreted matter element sinking into the burning zone obeys the equation $\mathrm{d}l/\mathrm{d}t = v(t)$. The number density of ^{34}Ne decreases slowly with time [$Y(t) \propto (t+\tau)^{-1}$] in correspondence to the quadratic decline of the reaction rate ($R \propto Y^2$).

To analyse the deep crustal heating in accreting neutron stars (Section 1), we mainly need the total energy generation power

$$W(t) \approx 4\pi R^2 \int_{l_1}^{l_{\rm max}} \mathrm{d}l\ Q(l), \tag{8}$$

where l_1 refers to the ^{34}Ne production threshold and $l_{\rm max}$ to the deepest position of accreted matter elements within the burning layer; $Q = Q_0\,R$ is the energy density release rate (Q_0 is the energy release in one reaction event corresponding to 0.4 MeV per one accreted nucleon). Taking R from equations (6) and (7) and replacing the integration over l by the integration over t, we have

$$W(t) = \frac{1}{\tau}\int_0^t \mathrm{d}t'\,\frac{W_0(t-t')}{[1 + (t-t')/\tau]^2}, \tag{9}$$

where

$$W_0(t) = 0.4\ \mathrm{MeV}\ \frac{\dot{M}(t)}{m_{\rm u}} \approx 2.43\times 10^{33}\ \dot{M}_{-10}(t)\ \mathrm{erg\,s^{-1}} \tag{10}$$

is the energy generation power for the case of ^{34}Ne instantly burning into ^{68}Ca, and $m_{\rm u}$ is the atomic mass unit. We assume here that the accretion starts at $t = 0$.

Equation (9) enables us to calculate $W(t)$ for any given mass accretion rate $\dot{M}(t)$. Note that the solution is linear in $\dot{M}(t)$. Therefore, an increase or a decrease of $\dot{M}(t)$ by a constant factor rescales $W(t)$ but does not change a temporal variability of $W(t)$. For a constant

$\dot{M} = \dot{M}_0$, we immediately obtain $W(t) = W_0 t/(t + \tau)$ which naturally gives the constant energy generation $W(t) = W_0$ for $t \gg \tau$. The burning time τ can be treated as a relaxation time in energy generation evolution.

For a sequence of accretion episodes $i = 1, 2, \ldots, N$ of constant mass accretion rates $\dot{M}_i$ (within every episode)

$$W(t) = \sum_{i=1}^{N} W_{0i}\, F(t - t_i), \tag{11}$$

where

$$\begin{aligned} F(t) &= \frac{\tau_i}{(t+\tau)[1+(t-\tau_i)/\tau]} \qquad \text{for } t > \tau_i, \\ F(t) &= \frac{t}{t+\tau} \qquad \text{for } 0 \leqslant t \leqslant \tau_i, \\ F(t) &= 0 \qquad \text{for } t < 0; \end{aligned} \tag{12}$$

W_{0i} is the value of W_0 for an episode i (see equation 10), t_i marks the onset of the episode i and τ_i is the duration of this episode.

3 BURNING TIME VERSUS QUIESCENCE DURATION

The crucial parameter of the theory is the ^{34}Ne burning time τ, which can be calculated from equation (6). Unfortunately, theoretical values of τ are highly uncertain due to several reasons. First, the uncertainties stem from the uncertainties in the parameters of equations (3) and (4) (see Table 1). These uncertainties are mostly associated with the problems of calculating the Coulomb tunnelling in the pycnonuclear regime. Also, they partly stem from our poor knowledge of the actual state of multicomponent strongly coupled ion mixtures (a uniform mix, a regular lattice structure, etc.; see Yakovlev et al. 2006 for details). Furthermore, there are uncertainties in the astrophysical S-factor related to nuclear physics. Specifically, we expect that the presence of an extended neutron halo in nuclei such as ^{34}Ne and the neglect of free neutrons outside the nuclei introduces an uncertainty of several orders of magnitude in the present estimate of the S-factor; these effects will be discussed in a separate paper (Gasques et al., in preparation) devoted to calculations of S-factors for a number of fusion reaction of astrophysical importance. Finally, the assumptions of the deep crustal heating theory of Haensel & Zdunik (1990) (e.g. a specific cold liquid drop model of atomic nuclei) can introduce uncertainties into the parameters of this theory, for instance, into the threshold density ρ_1 of ^{34}Ne production.

Some estimates of τ are given in Table 2. First, let the astrophysical factor be given by equation (5), and the ^{34}Ne production threshold be equal to ρ_1, but let us use different Coulomb-tunnelling models from Table 1. For the optimal, maximum- and minimum-rate models we obtain $\tau = 5.4$ h, 0.013 ms and 2.2 yr, respectively (the first three lines in Table 2). These burning times differ by many orders of magnitude because the Coulomb-tunnelling probability is extremely (exponentially) sensitive to the model parameters listed in Table 1. The time-scale of $\tau = 0.013$ ms corresponds to nearly instantaneous burning. The fusion process is so fast that the pycnonuclear burning of ^{40}Mg at $\rho < \rho_1^*$ (Section 2) may become efficient. This would prevent the ^{34}Ne production and modify the Haensel & Zdunik (1990) model of deep crustal heating.

Table 2. Estimates of ^{34}Ne burning time τ.

No.	Model from Table 1	S-factor	^{34}Ne-production threshold	τ
1	Optimal	Equation (5)	ρ_1	5.4 h
2	Maximum rate	Equation (5)	ρ_1	0.013 ms
3	Minimum rate	Equation (5)	ρ_1	2.2 yr
4	Optimal	Equation (5)$\times 10^{-2}$	ρ_1	23 d
5	Optimal	Equation (5)	$0.9\rho_1$	7.9 d

To demonstrate the effect of the S-factor, we can adopt the optimal Coulomb-tunnelling model, maintain the ^{34}Ne production threshold, but reduce S by two orders of magnitude. This gives us $\tau = 23$ d (scenario 4 in Table 2). Another example is provided by scenario 5 in Table 2, where we choose the optimal Coulomb-tunnelling model, the astrophysical factor from equation (5), but reduce the ^{34}Ne production threshold by 10 per cent. We obtain a burning time $\tau = 8$ d, approximately 35 times longer than for the non-reduced threshold, because the Coulomb-tunnelling probability decreases strongly (exponentially) with decreasing ρ.

These parameter variations show that the theoretical estimates of τ are, indeed, highly uncertain. Haensel & Zdunik (1990) restrained themselves to a fixed model of Coulomb tunnelling and to an S-factor, which was derived by a simple extrapolation of cross-sections for fusion reactions between nuclei near the stability line. They obtained $\tau \sim$ a few months, inside the interval of possible values of τ indicated above.

For illustration, Fig. 1 shows the temporal variability of the energy generation power due to the ^{34}Ne burning in response to a transient accretion with a one-year cycle (the accretion with the constant rate $\dot{M} = 10^{-10}\ \mathrm{M_\odot\ yr^{-1}}$ in the first two months of every year, followed by 10 months of quiescence). It is assumed that accretion starts at $t = 0$. Lines 1–5 present the energy generation rates for five scenarios of pycnonuclear burning listed in Table 2.

The dotted line 2 is for an almost instant burning; the burning rate is given by equation (10) during accretion episodes, and is negligibly small during quiescence. The solid line 1 is for the optimal Coulomb-tunnelling model. The burning time $\tau \approx 5.4$ h is much shorter than the accretion and quiescent periods. When accretion

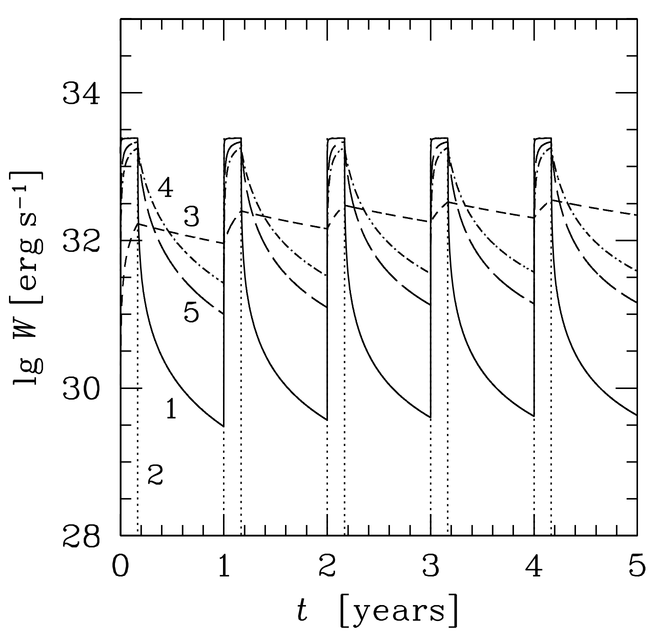

Figure 1. The energy generation power due to the ^{34}Ne burning in the course of transient accretion (with $\dot{M} = 10^{-10}\ \mathrm{M_\odot\ yr^{-1}}$ in two months of every year, followed by 10 months of quiescence). Lines 1–5 refer to corresponding scenarios in Table 2.

starts, the energy generation power saturates at the stationary level (10) within several hours. When accretion stops, the energy generation decays slowly ($W(t) \propto 1/\tilde{t}^2$, where $\tilde{t}$ is the time following the last accretion episode). This slow decay is caused by the suppression of the pycnonuclear burning in the matter with low abundance of ^{34}Ne (Section 2). Actually, this suppression may be stronger than that predicted by our pycnonuclear burning model (as discussed by Yakovlev et al. 2006). A small fraction of ^{34}Ne may survive for a long time producing a slow heating of the matter during quiescent periods. The short-dashed line 3 corresponds to the slowest theoretical Coulomb tunnelling of the reacting nuclei. The associated burning time $\tau = 2.2$ yr is longer than the accretion cycle, and the energy generation power is a slowly varying function of time. The energy generation has almost the same efficiency during the accretion and quiescent episodes; in the first approximation, it can be considered as constant (provided by the time-averaged mass accretion rate). Finally, the dot–dashed line 4 and the long-dashed line 5 refer to the burning scenarios with $\tau = 23$ and 8 d, respectively. They are intermediate between the scenarios 1 and 3, and produce a notable amount of heat during quiescent periods.

4 CONCLUSIONS

We have analysed the temporal variability of the nuclear energy generation power owing to the pycnonuclear burning of ^{34}Ne in the inner crust of a transiently accreting neutron star within the deep crustal heating model of Haensel & Zdunik (1990). Current models for nuclear fusion carry considerable uncertainties which translate into highly uncertain predictions of the burning time τ, ranging from a fraction of a millisecond to a few years. The uncertainties stem from the Coulomb-tunnelling problem in a dense plasma, from our poor knowledge of actual states of cold multicomponent ion mixtures, from the quantum mechanical probability of fusion between nuclei with neutron haloes in a dense matter containing free neutrons and from uncertainties inherent in the deep crustal heating model. Further theoretical studies are required to reduce these uncertainties in τ.

If the shortest possible values of τ turned out to be real, they would indicate that pycnonuclear reaction rates are actually much higher than those commonly accepted. This could lead to efficient pycnonuclear transformations (for instance, of ^{40}Mg at $\rho < \rho_1$), neglected in the classical scenarios of Haensel & Zdunik (1990, 2003); the scenarious might require modifications.

If the largest possible values of τ were true, the pycnonuclear energy generation in a neutron star crust would be slow, almost independent of time for a variable mass accretion rate. If so, the temporal variability of the nuclear energy generation owing to a variable accretion would be absent and could not be responsible for the observed temporal variability of the thermal radiation from neutron stars in SXTs during quiescent periods. Some data on the observed variability of the SXTs Cen X-4, Aql X-1, 4U 2129+37 are collected, for instance, by Ushomirsky & Rutledge (2001). A recent review of observations of these and other sources is given by Wijnands (2005). Note that neutron stars in some SXTs in certain quiescent periods are so cold that no thermal emission component is detected [as reported by Campana et al. (2002) for SAX J1808.4−3658 and by Jonker et al. (2006) for 1H 1905+000]. Recently Cackett et al. (2006) presented very interesting *Chandra* and *XMM–Newton* X-ray observations of two SXTs, KS 1731−260 and MXB 1659−29, over approximately 4 yr in which the SXTs returned from active to quiescent states (with the transition time of the order of 1 yr). These first detailed observations of the transition to quiescent states should be most valuable for testing the theory of deep crustal heating of accreted matter.

Until now observed temporal variability of radiation from SXTs has been analysed (e.g. Colpi et al. 2001; Ushomirsky & Rutledge 2001) assuming an instant nuclear energy release in response to a variable mass accretion. We have shown that the nuclear energy release is not instant for many pycnonuclear burning models; a substantial amount of energy is released during quiescent periods. This should be taken into account while simulating the thermal diffusion of heat from the deep crustal heating sources to the neutron star surface and while calculating thus the surface thermal luminosity. Although these problems are out the scope of this paper, we note that, actually, one should deal with two characteristic time-scales, associated with nuclear burning and thermal diffusion.

The thermal diffusion time-scale has been estimated by Ushomirsky & Rutledge (2001). As follows from their fig. 3, in the case of ^{34}Ne burning the diffusion time-scale varies from $\sim$10 d to a few years, depending on the mass accretion rate and the thermal state of a star (cold or hot). Let us remark that Ushomirsky & Rutledge (2001) neglected the effects of neutron heat conduction and neutron superfluidity in the inner neutron star crust. These effects can further complicate the problem. The thermal conductivity of free neutrons in the inner crust is almost unexplored. It can be efficient and shorten the thermal diffusion time-scale. Moreover, it is widely accepted that free neutrons can be in superfluid state (e.g. Lombardo & Schulze 2001). Neutron superfluidity can strongly intensify neutron heat transport. The effect can be similar to that in superfluid ^{4}He, where no temperature gradients can be created in laboratory experiments because they are immediately smeared out by responding convective flows (e.g. Tilley & Tilley 1990). In addition, neutron superfluidity initiates a strong neutrino emission due to Cooper pairing of neutrons (Flowers, Ruderman & Sutherland 1976) which affects thermal diffusion in a warm crust even if neutron conduction is neglected (Cumming et al. 2006). Therefore, the thermal diffusion time-scales seem complicated functions of neutron star parameters which are currently rather uncertain.

In this paper, we have focused on the ^{34}Ne burning in the scenario of Haensel & Zdunik (1990). Similar problems can be formulated with regard to other pycnonuclear reactions in the crust of an accreting neutron star. Their solutions would lead to a construction of consistent models of accreted neutron star crust, deep crustal heating and related observational phenomena.

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