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Neutron star cooling after deep crustal heating in the X-ray transient KS 1731–260

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ABSTRACT
We simulate the cooling of the neutron star in the X-ray transient KS 1731−260 after the source returned to quiescence in 2001 from a long ($\gtrsim$12.5 yr) outburst state. We show that the cooling can be explained assuming that the crust underwent deep heating during the outburst stage. In our best theoretical scenario the neutron star has no enhanced neutrino emission in the core, and its crust is thin, superfluid, and has the normal thermal conductivity. The thermal afterburst crust–core relaxation in the star may not be over.

Key words: stars: neutron – X-rays: individual: KS 1731−260.

1 INTRODUCTION

KS 1731−260 is a neutron star X-ray transient whose observational history has been described recently by Cackett et al. (2006). The source was discovered in the active state in 1989 August by the *Kvant* orbital observatory; subsequent analysis showed that it had also been active in 1988 October (Sunyaev et al. 1990). It remained a bright X-ray source showing type I X-ray bursts for about 12.5 yr. It is believed that this activity was powered by accretion on to the neutron star (through an accretion disc) from its low-mass companion in a compact binary. The source remained active until the beginning of 2001 and then returned to quiescence. The last detection in the active state was made on 2001 January 21 with the *Rossi X-ray Timing Explorer* (*RXTE*), but by 2001 February 7, *RXTE* failed to detect KS 1731−260 in the active state (Wijnands et al. 2001).

The first detection of KS 1731−260 in quiescence was made by Wijnands et al. (2001) with *Chandra* on 2001 March 27. For D = 7 kpc, the 0.5–10 keV luminosity was $\sim 10^{33}$ erg s^{-1}, 3–4 orders of magnitude lower than in the active state. The radiation spectrum contains a component that can be interpreted as the thermal emission from the neutron star surface. Since then the source has been observed several times with *Chandra* and *XMM–Newton*, as summarized by Cackett et al. (2006). Its X-ray light curve faded over a time-scale ∼2 yr showing a trend to flattening (with the residual luminosity of $\sim 2 \times 10^{32}$ erg s^{-1}).

According to observations, the accretion in quiescent states of X-ray transients is stopped or strongly suppressed. The nature of quiescent X-ray emission is a subject of debates (see Cackett et al. 2006 and references therein for a list of possible hypotheses). Here, we focus on the hypothesis of deep crustal heating of neutron stars proposed by Brown, Bildsten & Rutledge (1998). It states that when a neutron star accretes, its crust is heated by nuclear transformations (mainly by beta captures and pycnonuclear reactions) in the accreted matter sinking within the crust under the weight of newly accreted material. The star remains sufficiently warm after an accretion episode, producing quiescent surface emission. The sequence of nuclear transformations and associated energy generation rates were calculated by Haensel & Zdunik (1990) assuming that the accreted matter burns to ^{56}Fe in the neutron star surface layers so that, initially, before sinking within the deep crust, the matter is composed of ^{56}Fe. Later, Schatz et al. (2001) calculated explosive nucleosynthesis in the neutron star surface layers and showed that the explosive burning can progress to much heavier elements. Accordingly, Haensel & Zdunik (2003) proposed new deep crustal heating scenarios (starting with heavier elements, particularly, with^{106}Pd). In all the cases Haensel & Zdunik (1990, 2003) obtained similar deep crustal energy releases, ∼1–1.5 MeV per accreted nucleon, sufficient to power quiescent thermal emission in X-ray transients. Recently Gupta et al. (2007) have reconsidered the heating starting with multicomponent matter (ashes of explosive burning in the surface layers). They have shown that the heating of the deep outer crust can be higher because beta captures can produce daughter nuclei in excited states; their de-excitation can generate extra heat.

The onset of the quiescent state of KS 1731−260 was recognized as an outstanding phenomenon from the very beginning. The majority of other X-ray transients undergo short accretion episodes (days to months) in which the deep crustal heating cannot break the crust–core thermal coupling and make the crust much hotter than the stellar core. However, it is possible in KS 1731−260 because of the long accretion stage (Rutledge et al. 2002). Therefore, observations of its quiescent thermal emission can help to understand

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how the crustal heat spreads over the entire star; this is useful for exploring the neutron star structure.

The first modelling of the KS 1731−260 cooling was performed by Rutledge et al. (2002) soon after the quiescence onset. The authors based their work on previous simulations by Ushomirsky & Rutledge (2001) of the crust–core relaxation in a neutron star with a heated crust. Rutledge et al. (2002) proposed several cooling scenarios based on the deep crustal heating model of Haensel & Zdunik (1990) and different crust and core microphysics. They predicted that the neutron star can reach the crust–core relaxation and associated flattening of the quiescent soft X-ray light curve in 1–30 yr. Cackett et al. (2006) have compared the new observations of KS 1731−260 with the predictions of Rutledge et al. (2002) and conclude that the star should have high thermal conductivity in the crust and enhanced neutrino emission in the core.

Here we present new cooling calculations and discuss their consistency with the observations of KS 1731−260.

2 COOLING MODEL AND PHYSICS INPUT

Our cooling simulations are similar to those of Ushomirsky & Rutledge (2001) and Rutledge et al. (2002). We assume that the neutron star crust underwent deep crustal heating during the long accretion stage. We employ the model of deep crustal heating of Haensel & Zdunik (1990), modified by Haensel & Zdunik (2007) for a better description of sequences of pairs of beta-captures in the crust. It is now assumed that daughter nuclei after a primary beta capture are produced in excited states and de-excite before a secondary beta capture, thus heating the matter (instead of wasting extra energy in neutrino emission). In this way the distribution of heating sources remains the same as in Haensel & Zdunik (1990) but the sources in the outer crust become stronger, resembling those obtained by Gupta et al. (2007). The source positions and strengths, calculated by Haensel & Zdunik (2007), are shown in Fig. 1. The overall energy release is 1.9 MeV per accreted nucleon.

To simulate the neutron star cooling we use our general relativistic cooling code (Gnedin, Yakovlev & Potekhin 2001). It solves the thermal diffusion problem within the star (at densities $\rho > \rho_b$) and

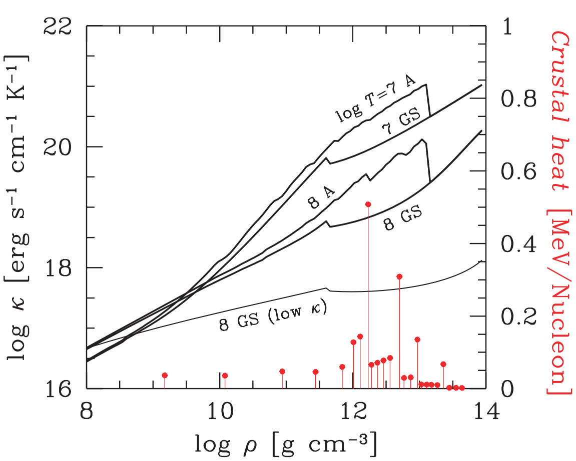

Figure 1. Density dependence of the electron thermal conductivity κ (left-hand vertical scale) in the neutron star crust with accreted (A) or ground-state (GS) matter at two temperatures ($\log T$[K] = 7 and 8, numbers next to curves). The thin lower curve is for the model of low κ while other curves are for normal κ. Vertical bars show positions and power (right vertical scale) of the heat sources. The initial layer is assumed to consist of ^{56}Fe, as in Haensel & Zdunik (1990), but neutrino losses in electron captures are suppressed, following Gupta et al. (2007).

uses a predetermined quasi-stationary relation $T_s - T_b$ (Potekhin, Chabrier & Yakovlev 1997) between the effective surface temperature T_s and the temperature T_b at the base ($\rho = \rho_b$) of a thin heat-blanketing envelope ($\rho \leqslant \rho_b$). Now we shift ρ_b from previously used values $\sim 10^{10}$–10^{11} g cm^{-3} to $\rho_b = 10^8$ g cm^{-3}. This allows us to put all heat sources into the region of $\rho > \rho_b$ and to reduce the time of heat propagation through the blanketing layer from ∼1 yr to ∼1 d (enabling the code to trace short-term – 1 d – surface temperature variations).

To explore the sensitivity of calculations to the crust physics, we employ two models of the neutron star crust, composed of ground-state (GS) or accreted (A) matter. The ground-state crust (e.g. Haensel, Potekhin & Yakovlev 2007) has been used in our previous simulations. The model of accreted crust (Haensel & Zdunik 1990) is consistent with the adopted model of deep crustal heating. The accreted crust is composed of lighter nuclei with lower atomic numbers. Deep in the inner crust, at $\rho \gtrsim 10^{13}$ g cm^{-3}, composition is similar to the ground-state one, with $\gtrsim$80 per cent of nucleons constituting a neutron gas (Haensel & Zdunik 1990).

We employ the electron thermal conductivity in the crust, κ, limited by electron–ion (Gnedin et al. 2001) and electron–electron (Shternin & Yakovlev 2006) scattering. It will be called *normal*. We will also use the model electron thermal conductivity proposed by Brown (2000). It corresponds to an amorphous crust (e.g. Jones 2004) and will be called *low*. In fact, it gives the lowest limit on κ in the crust. Several model thermal conductivities as functions of density in the crust for two values of temperature ($T = 10^8$ and 10^7 K) are plotted in Fig. 1.

In the inner crust, we take into account the effects of neutron superfluidity on the heat capacity of free neutrons (e.g. Yakovlev, Levenfish & Shibanov 1999). A representative set of models for superfluid neutron gaps in the inner crust, which determine superfluid critical temperature profiles $T_c(\rho)$, is collected by Lombardo & Schulze (2001). The collection includes a well-defined gap provided by the pure Bardeen–Cooper–Schrieffer (BCS) theory of singlet-state neutron pairing (with a maximum of $T_c \sim 2 \times 10^{10}$ K within the crust) and a number of gaps calculated using various neutron polarization models (with the maxima of T_c approximately three times lower). BCS superfluidity very strongly suppresses the neutron heat capacity in the inner crust; this superfluidity will be called *strong*. The effects of other superfluid models are weaker and more or less similar. For illustration of the latter effects, we will use the model proposed by Wambach, Ainsworth & Pines (1993); such superfluidity will be called *moderate*. We calculate the neutrino emission in the crust and in the core according to Yakovlev et al. (2001). In our cooling models the neutron star stays not too hot, so that crustal neutrino emission (including that due to Cooper pairing of neutrons) is insignificant.

In the neutron star core, we use an equation of state of dense matter (containing nucleons, electrons, and muons) constructed by Akmal, Pandharipande & Ravenhall (1998) (their model Argonne V18+δv+UIX*). Specifically, we adopt its convenient parametrization proposed by Heiselberg & Hjorth-Jensen (1999) and called ‘APR I’ by Gusakov et al. (2005). In this case, the maximum gravitational mass of stable neutron stars is $M_{max} = 1.923\,M_\odot$ and the direct Urca process of powerful neutrino emission opens at $M > 1.828\,M_\odot$. We will mainly use two neutron star models, with masses $M = 1.6$ and $1.4\,M_\odot$, where direct Urca process is forbidden; both stars demonstrate slow neutrino cooling via the modified Urca process. The $1.4 - M_\odot$ star has the central density $\rho_c = 9.4 \times 10^{14}$ g cm^{-3}, the circumferential radius $R = 12.14$ km, and the crust thickness $\Delta R = R - R_{core} = 1.16$ km (where R_{core} is the core radius corresponding to $\rho = 1.5 \times 10^{14}$ g cm^{-3}). The 1.6-M$_\odot$ star is more compact, with a thinner crust, and has $\rho_c = 1.16 \times 10^{15}$ g cm^{-3}, $R = 11.88$ km and $\Delta R = 890$ m.

The thermal conductivity of the neutron star core is described following Baiko, Haensel & Yakovlev (2001) and Shternin & Yakovlev (2007). For simplicity, the effects of nucleon superfluidity in the core are neglected.

3 RESULTS AND DISCUSSION

We have calculated (Fig. 2) a number of cooling curves which give the effective surface temperatures T_s^∞, as detected by a distant observer, versus time t; $t = 0$ refers to 2001 February 1, the date near which KS 1731−260 turned in quiescence. We compare the curves with seven observational points presented by Cackett et al. (2006); the values of T_s^∞ were inferred from the observed X-ray spectra (employing non-magnetic neutron star hydrogen atmosphere models from the XSPEC data base and assuming $D = 7$ kpc, R = 10 km and $M = 1.4\,$M$_\odot$). We doubled the reported 1σ observational error bars to enlarge statistical significance, which would make our analysis more realistic.

To start any cooling calculation, we take a neutron star model with the thermally relaxed interior and some initial surface temperature T_{s0}^∞. Then we switch on deep crustal heating produced by a constant mass accretion rate $\dot{M}$ over 12.5 yr. In that period a certain amount of heat, $E_{\rm tot}$, is deposited into the crust. The crust is heated and its thermal balance with the thermally inertial core is violated. Then we switch off accretion (deep crustal heating) and the crust cools down regaining thermal equilibrium with the core. Some (typically small) part of $E_{\rm tot}$ diffuses to the surface and radiates away via thermal surface emission. The rest is carried by thermal conduction to the core. The core temperature stays almost unchanged because of the high core thermal conductivity and heat capacity. The crust–core thermal relaxation takes 1–100 yr, depending on the neutron star model. After this relaxation is over, the surface temperature almost reaches its initial value T_{s0}^∞. The star cools down further with isothermal interior over typical cooling time-scales 1–10 kyr until the next accretion episode. The extra heat deposited to the core is mainly emitted over those long cooling time-scales via core neutrino emission.

Our cooling curves in Fig. 2 are calculated for different neutron star masses, microphysics in the crust, mass accretion rates (and $E_{\rm tot}$), and T_{s0}^∞ (as shown in the figure and Table 1). Our aim is to explain the observed temporal evolution $T_s^\infty(t)$ of KS 1731−260 in the quiescent state. A successful explanation should also be consistent with the observational constraint on the mass accretion rate, $\dot{M} \lesssim 5 \times 10^{-9}\,M_\odot$ yr^{-1} (for $D = 8$ kpc, see table 3 in Yakovlev, Levenfish & Haensel 2003), which translates into $E_{\rm tot} \lesssim 2.4 \times 10^{44}$ erg for the adopted deep heating model. Table 1 shows that all presented cooling models roughly satisfy this requirement.

Table 1. Cooling curves in Fig. 2.

Curve	T_{s0}^∞ MK	Crust model	Conduction in crust	Superfluid in crust	$E_{\rm tot}$ 10^{44} erg
1a	0.8	A	normal	moderate	2.6
2a	0.8	GS	normal	none	1.9
3a	0.8	GS	normal	moderate	1.8
4a	0.8	A	normal	strong	2.6
5a	0.8	A	low	moderate	0.6
6a	0.8	A	normal	moderate	1.9
1b	0.8	A	normal	moderate	2.3
2b	0.8	GS	normal	none	1.7
3b	0.8	GS	normal	moderate	1.5
1c	0.67	GS	normal	none	2.4
2c	0.63	GS	normal	none	2.4

Fig. 2(a) refers to the 1.6-M$_\odot$ star neutron star model, while Fig. 2(b) is for the 1.4-M$_\odot$ star. All curves in Figs 2(a) and (b) are calculated assuming the initial surface temperature to be $T_{s0}^\infty =$ 0.8 MK (so that the internal temperature is $\sim 8 \times 10^7$ K, as it would be in a cooling isolated neutron star which is $\sim 10^5$ yr old). This is a typical surface temperature of the neutron star provided by the last three observational points. Thus, in Figs 2(a) and (b) we (following Cackett et al. 2006) tacitly assume that the crust–core equilibrium is re-established in two years after the quiescence onset. In all curves but curve 6 in Figs 2(a) and (b) $E_{\rm tot}$ has been chosen in such a way that the surface temperature at the first quiescent observation is consistent with data.

Curve 1 in Fig. 2(a) seems to be the best. It corresponds to the accreted crust with the normal thermal conductivity and moderate neutron superfluidity. It naturally explains the thermal relaxation of KS 1731−260 with the standard physics input. The maximum internal temperature rise to $T \sim 4 \times 10^8$ K takes place at $t = 0$ near the boundary between the outer and the inner crust. The core–crust relaxation takes $\sim$2 yr. The star would need $\sim 10^3$ yr to emit all the heat pumped into the core during the outburst and reach the same

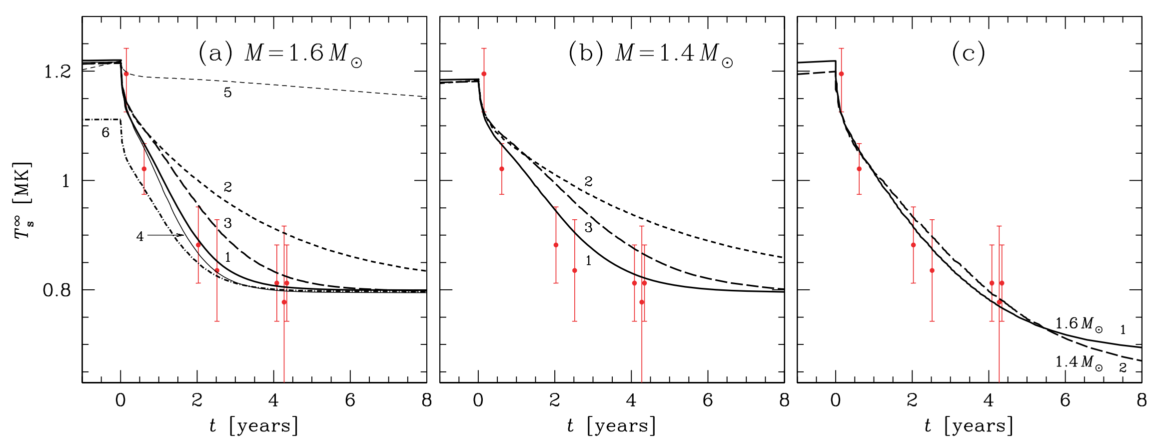

Figure 2. Theoretical cooling curves for (a) $M = 1.6$-M$_\odot$ and (b) 1.4-M$_\odot$ neutron stars, and (c) for stars with both M compared with observations. The curves are explained in Table 1 and in the text.

thermal state as before the outburst. This is in good agreement with the estimate of Rutledge et al. (2002) for a similar cooling model.

Using the same physics as for curve 1 but for the ground-state crust (with lower conductivity) we obtain slower relaxation (curve 3). It is acceptable but less consistent with the observations; it requires lower $E_{\rm tot}$ because it is easier to heat the crust with smaller thermal conductivity. Taking the latter cooling model 3 and neglecting superfluidity in the inner crust, we obtain curve 2. A non-superfluid crust has larger (neutron) heat capacity which noticeably delays the thermal relaxation making it much less consistent with the data. Returning to our best model 1 but assuming strong superfluidity in the crust, we suppress more strongly the heat capacity of neutrons and obtain curve 4; it shows faster and quite acceptable relaxation. The effects of strong and moderate superfluidity are actually very similar, although the presence of superfluidity greatly improves the agreement with the data. Now if we return to model 1 but assume low thermal conductivity, we see much longer crust–core relaxation (over several hundred years, curve 5). It is inconsistent with the observations, in agreement with the conclusion of Cackett et al. (2006). Finally, if we take the best model 1 but assume the same (lower) mass accretion rate as in model 2, we get curve 6. Therefore, the latter mass accretion rate, being used for the microphysics of model 1, is insufficient to explain high values of $T_{\rm s}^{\infty}$ in the beginning of the quiescent state.

Curves 1–3 in Fig. 2(b) are analogous to curves 1–3 in Fig. 2(a), but are calculated for a less massive star, with a thicker crust. The thicker crust produces longer thermal relaxation, which is less consistent with the observations.

We have also performed many other cooling calculations varying the physics input. In particular, we have varied the distribution of heat sources within the crust. We have seen that it is much easier to explain the observations by placing the sources in the outer crust. These models naturally give short thermal relaxation and efficient heating of the surface. In contrast, were all sources located in the deep inner crust, the star would show longer thermal relaxation and one would need too much energy to heat the surface because the heat would be pumped into the core. In connection to this, the improved model of deep crustal heating used here, where the heat release in the crust is enhanced compared to the original model of Haensel & Zdunik (1990) (due to switching-off neutrino losses associated with electron captures, Gupta et al. 2007), is more favourable for explaining the observations.

In addition, we have artificially varied the thermal conductivity in different places of the crust and found high sensitivity of the cooling curves to these variations. The conductivity strongly affects both the thermal relaxation time and the efficiency of surface heating. Taking the conductivity a few times lower than the normal conductivity of accreted or ground-state crust produces crust–core relaxation that takes too long and which disagrees with the data.

Furthermore, we have studied different neutron star models (different equations of state in the core, and different masses). In particular, we have used the models of massive neutron stars whose core neutrino emission is strongly enhanced by the nucleonic direct Urca process (e.g. a 1.9-$\mathrm{M}_{\odot}$ model for the equation of state employed in Fig. 2). We have found that we need unrealistically intense crustal heating (too high an $E_{\rm tot}$) to explain the high observed values of $T_{\rm s}^{\infty}(t)$ in the beginning of quiescence. Moreover, such a star has too short a global cooling time-scale (years to decades), comparable to the crust–core relaxation time. The crust–core relaxation becomes coupled to the global thermal relaxation; the cooling curves do not show the observed flattening at $t \gtrsim 2$ yr. Hence, we cannot reconcile theory with observations if the neutrino emission of the star is enhanced by the direct Urca process. Nevertheless, we think that it may be possible to explain the observations if the neutrino emission is enhanced by a less efficient mechanism (e.g. by pion or kaon condensation in the stellar core) or if the direct Urca process operates but is strongly suppressed by nucleon superfluidity (e.g. Yakovlev & Pethick 2004; Page, Geppert & Weber 2006).

Finally, we remark that the thermal crust–core relaxation in KS 1731−260 may still not be over. This is illustrated in Fig. 2(c), where we present two new cooling curves for our 1.6-$\mathrm{M}_{\odot}$ star and 1.4-$\mathrm{M}_{\odot}$ neutron star models. They are calculated without imposing the constraint that $T_{\rm s0}^{\infty} = 0.8$ MK. We have intentionally taken the physics input (ground-state, non-superfluid crust with normal conductivity) which gives too long a thermal relaxation time to explain the data for the scenarios in Figs 2(a) and (b). Now we take lower $T_{\rm s0}^{\infty}$ and reach consistency with the current observations (and get a rather low crustal heat release $E_{\rm tot}$). We see that the crust–core relaxation in KS 1731−260 can really last longer than 2 yr, and this possibility widens the class of cooling models consistent with the data. It will hopefully be checked in future observations of KS 1731−260.

4 CONCLUSIONS

We have simulated the cooling of the neutron star in the quiescent state of KS 1731−260 by employing the model of deep crustal heating of the star in the outburst state. We have used the model of deep crustal heating (Haensel & Zdunik 1990) updated by switching-off neutrino losses in the crust (Gupta et al. 2007). Our main conclusions are as follows.

(i) One can explain current observations of KS 1731−260 using a model of deep crustal heating and a standard microphysics of the neutron star.

(ii) If the crust–core thermal relaxation in the neutron star is reached in $\sim$2 yr, the most successful cooling model implies the model of accreted crust with normal thermal conductivity and neutron superfluidity; the neutron star should be sufficiently massive (to have a thinner crust), but the neutrino emission in its core cannot be too high (e.g. it can be provided by the modified Urca process). All these factors shorten the crust–core thermal relaxation.

(iii) The model of low thermal conductivity (amorphous crust) gives too long a crust–core relaxation time, inconsistent with the data.

(iv) The enhanced neutrino cooling via the direct Urca process in the neutron star core gives cooling of the entire star that is too fast and requires crustal heating that is too intense, inconsistent with the data.

(v) The crust–core thermal relaxation may not be reached yet. If so, the data can be explained by a wider class of neutron star models.

We stress that the thermal crust–core relaxation of the neutron star in KS 1731−260 is much more sensitive to the physics of the crust than the core. We employed the models of non-superfluid core just for simplicity. Core superfluidity can change the core heat capacity and neutrino luminosity, but the principal conclusions will be the same. Our calculations are not entirely self-consistent. For instance, the surface temperature was inferred from observations (Cackett et al. 2006), assuming neutron star masses and radii different from those used in our cooling models. This inconsistency cannot affect our main conclusions, but it would be desirable to infer $T_{\rm s}^{\infty}$ for our neutron star models. The thermal relaxation in the quiescent state has been observed also (Cackett et al. 2006) for another neutron star X-ray transient, MXB 1659–29. We hope to analyse these data in the next publication.

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REFERENCES

Akmal A., Pandharipande V. R., Ravenhall D. G., 1998, Phys. Rev. C, 58, 1804

Baiko D. A., Haensel P., Yakovlev D. G., 2001, A&A, 374, 151

Brown E. F., 2000, ApJ, 531, 988

Brown E. F., Bildsten L., Rutledge R. E., 1998, ApJ, 504, L95

Cackett E. M., Wijnands R., Linares M., Miller J. M., Homan J., Lewin W. H. G., 2006, MNRAS, 372, 479

Gnedin O. Y., Yakovlev D. G., Potekhin A. Y., 2001, MNRAS, 324, 725

Gupta S., Brown E. F., Schatz H., Möller P., Kratz K.-L., 2007, ApJ, 662, 1188

Gusakov M. E., Kaminker A. D., Yakovlev D. G., Gnedin O. Y., 2005, MNRAS, 363, 555

Haensel P., Zdunik J. L., 1990, A&A, 227, 431

Haensel P., Zdunik J. L., 2003, A&A, 404, L33

Haensel P., Zdunik J. L., 2007, A&A, submitted (arXiv: 0708.3996)

Haensel P., Potekhin A. Y., Yakovlev D. G., 2007, eds, Astrophys. Space Sci. Library Vol. 326, Neutron Stars 1. Equation of State and Structure. Springer, New-York

Heiselberg H., Hjorth-Jensen M., 1999, ApJ, 525, L45

Jones P. B., 2004, MNRAS, 351, 956

Lombardo U., Schulze H.-J., 2001, Lecture Notes Phys., 578, 30

Page D., Geppert U., Weber F., 2006, Nucl. Phys. A, 777, 497

Potekhin A. Y., Chabrier G., Yakovlev D. G., 1997, A&A, 323, 415

Rutledge R. E., Bildsten L., Brown E. F., Pavlov G. G., Zavlin V. E., Ushomirsky G., 2002, ApJ, 580, 413

Schatz H. et al., 2001, Phys. Rev. Lett., 86, 3471

Shternin P. S., Yakovlev D. G., 2006, Phys. Rev. D, 74, 043004

Shternin P. S., Yakovlev D. G., 2007, Phys. Rev. D, 75, 103004

Sunyaev R. A. et al., 1990, SvA Lett., 16, 59

Ushomirsky G., Rutledge R. E., 2001, MNRAS, 325, 1157

Wambach J., Ainsworth T. L., Pines D., 1993, Nucl. Phys. A, 555, 128

Wijnands R., Miller J. M., Markwardt C., Lewin W. H. G., van der Klis M., 2001, ApJ, 560, L159

Yakovlev D. G., Pethick C. J., 2004, ARA&A, 42, 169

Yakovlev D. G., Levenfish K. P., Shibanov Yu. A., 1999, Phys. Usp., 42, 737

Yakovlev D. G., Kaminker A. D., Haensel P., Gnedin O. Y., 2001, Phys. Rep., 354, 1

Yakovlev D. G., Levenfish K. P., Haensel P., 2003, A&A, 407, 265