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ORIGINAL ARTICLE

Cooling of magnetars with internal layer heating

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Abstract We model thermal evolution of magnetars with a phenomenological heat source in a spherical internal layer and compare the results with observations of persistent thermal radiation from magnetars. We show that the heat source should be located in the outer magnetar's crust, at densities $\rho \lesssim 5 \times 10^{11}$ g cm^{-3}, and the heating rate should be $\sim 10^{20}$ erg cm^{-3} s^{-1}. Heating deeper layers is extremely inefficient because the thermal energy is mainly radiated away by neutrinos and does not warm up the surface to the magnetar's level. This deep heating requires too much energy; it is inconsistent with the energy budget of neutron stars.

Keywords Dense matter—stars · Magnetic fields—stars · Neutron—neutrinos

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1 Introduction

It is likely that soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) belong to the same class of objects, *magnetars*, which are relatively hot, isolated slowly rotating neutron stars of age $t \lesssim 10^5$ yr with unusually strong magnetic fields, $B \gtrsim 10^{14}$ G (see, e.g., Woods and Thompson 2006, for a recent review). There have been numerous attempts to explain the activity of these sources and the high level of their X-ray emission by the release of the magnetic energy in their interiors, but a reliable theory is still absent.

In this paper we study the thermal evolution of magnetars as cooling isolated neutron stars. We do not develop a self-consistent theory of the magnetar thermal structure and evolution but use a simplified phenomenological approach which allows us to draw definite model-independent conclusions. We show that magnetars are too warm and cannot be purely cooling neutron stars; they should have some additional heating source, which we assume to operate in magnetar interiors. We determine the parameters of the heating source (its location and power) which are consistent with the high level of observed thermal radiation of SGRs and AXPs and with the energy budget of an isolated neutron star. We will mainly follow the consideration of our recent paper (Kaminker et al. 2006).

2 Observational data

For comparing theoretical calculations with observations, we select the same seven magnetar sources—two SGRs and five AXPs—as in Kaminker et al. (2006). We take the estimates of their spindown ages t, surface magnetic fields B and the blackbody surface temperatures T_s^∞ (redshifted for

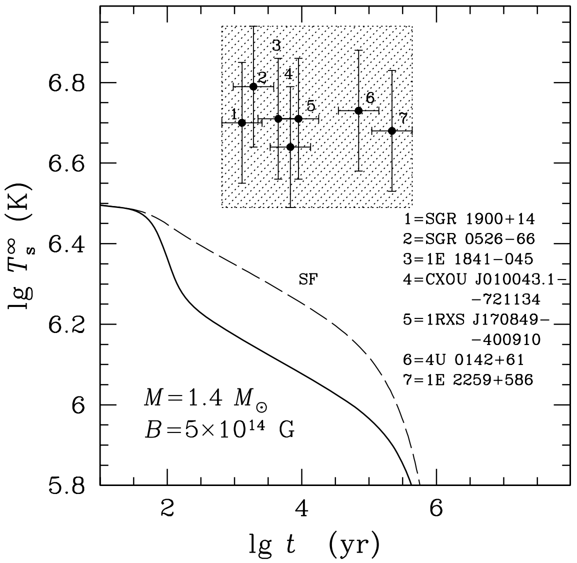

Fig. 1 Blackbody surface temperatures T_s^∞ and ages t of two SXTs and five AXPs (from Kaminker et al. 2006). The shaded rectangle is the "magnetar box". The observational data are compared to theoretical cooling curves of the $1.4M_\odot$ neutron star with the magnetic field $B = 5 \times 10^{14}$ G and no internal heating sources; the star is either non-superfluid (the *solid line*) or has strong proton superfluidity in the core (the *dashed line SF*)

a distant observer) from Tables 14.1 and 14.2 of the review paper by Woods and Thompson (2006) and from the original paper by McGarry et al. (2005). The selected data are displayed in Fig. 1. The original publications which report these data are:

1. SGR 1900+14—Woods et al. (2001, 2002)
2. SGR 0526-66—Kulkarni et al. (2003)
3. 1E 1841-045—Gotthelf et al. (2002) and Morii et al. (2003)
4. CXOU J010043.1-721134—McGarry et al. (2005)
5. 1RXS J170849-400910—Gavriil and Kaspi (2002) and Rea et al. (2003)
6. 4U 0142+61—Gavriil and Kaspi (2002) and Patel et al. (2003)
7. 1E 2259+586—Gavriil and Kaspi (2002) and Woods et al. (2004)

Because the estimates of T_s^∞ for SGR 1627-41 are absent we do not include this SGR in our data set. Also, we do not include SGR 1806-20 and several AXPs whose thermal emission component and characteristic age are less certain. The pulsed fraction of radiation from the selected sources is $\lesssim$20%, and the pulsed fraction from some of them is even lower ($\lesssim$10%). This may mean that the thermal radiation can be emitted from a substantial part of the surface, although the pulsed fraction can be lowered by the gravitational lensing effect.

Figure 1 shows the blackbody surface temperatures T_s^∞ of the selected SGRs and AXPs versus their spindown ages t. Woods and Thompson (2006) present the values of T_s^∞ and t without formal errors, whereas the actual errors are certainly large. We introduce, somewhat arbitrarily, the 30% errorbars to the values of T_s^∞ and a factor of 2 uncertainties into the values of t. The data are too uncertain and our theoretical models are too simplified to study every source separately. Instead, we attempt to understand the existence of magnetars as cooling neutron stars that belong to the "magnetar box", the shaded rectangle in Fig. 1. We assume that the data reflect an average persistent thermal emission from magnetars (excluding bursting states). Two theoretical cooling curves in Fig. 1 are explained in Sect. 4.

3 Physics input

Calculations have been performed with our general relativistic cooling code (Gnedin et al. 2001). It models the thermal evolution of an isolated neutron star by solving the equations of heat diffusion within the star. The code takes into account heat outflow via neutrino emission from the entire stellar body and via energy transport within the star, leading to thermal photon emission from the surface. To simplify calculations, the star is artificially divided (e.g., Gudmundsson et al. 1983) into a thin outer heat blanketing envelope and the bulk interior. The blanketing envelope extends from the surface to the layer of density $\rho = \rho_b \sim 10^{10}$–$10^{11}$ g cm^{-3}; its thickness is of a few hundred meters. In the blanketing envelope the code uses the solution of the stationary thermal diffusion problem obtained in the approximation of a thin plane-parallel layer for a dipole magnetic field configuration (neglecting neutrino emission). This solution relates temperature T_b at the bottom of the blanketing envelope ($\rho = \rho_b$) to the effective surface temperature T_s averaged over the neutron star surface (e.g., Potekhin and Yakovlev 2001; Potekhin et al. 2003). In the bulk interior ($\rho > \rho_b$) the code solves the full set of equations of thermal diffusion in the spherically symmetric approximation, neglecting the effects of magnetic fields on thermal conduction and neutrino emission.

In the calculations we have mainly used the T_b–T_s relation obtained specifically for simulating the magnetar evolution. The relation has been derived assuming $\rho_b = 10^{10}$ g cm^{-3} and the magnetized blanketing envelope made of iron. (In principle, the envelope may contain lighter elements provided by accretion; we will consider this case elsewhere but do not expect to obtain qualitatively different results.) The calculations show (Sect. 4) that magnetars are hot inside and have large temperature gradients extending deeply within the heat blanketing envelope. Accordingly, even high magnetar magnetic fields do not drastically influence the average thermal flux emergent through the blanketing envelope and the T_b–T_s relation (see, e.g., Potekhin et al. 2003). For certainty, we mainly assume the dipole magnetic field in the blanketing envelope with $B = 5 \times 10^{14}$ G at the magnetic poles. Some variations of B will not change our principal conclusions (Kaminker et al. 2006).

We expect that an anisotropy of heat transport, induced by the magnetic field in a warm magnetar crust at $\rho > \rho_b$, is not too high to dramatically modify the temperature distribution in the bulk of the star and to produce large deviations of this distribution from spherical symmetry (Kaminker et al. 2006). At lower temperatures the anisotropy would be much stronger and the effects of the magnetic field in the stellar bulk could be much more significant (Geppert et al. 2004, 2006).

Our standard cooling code takes into account the effects of magnetic fields only in the heat blanketing envelope. In this paper we have also included, in a phenomenological way, the effects of magnetic fields on the thermal evolution in the bulk of the star. For this purpose we have introduced a heat source located within a spherical layer at $\rho > \rho_b$ and associated possibly with the magnetic field (Sect. 5). The heating rate H [erg cm^{-3} s^{-1}] has been taken in the form

$$H = H_0 \Theta(\rho_1, \rho_2) \exp(-t/\tau), \tag{1}$$

where H_0 is the maximum rate, $\Theta(\rho_1, \rho_2)$ is a step-like function ($\Theta \approx 1$ in the heating layer, $\rho_1 < \rho < \rho_2$; and $\Theta \approx 0$ outside this layer, with a sharp but continuous transitions at the boundaries of the layer), t is the stellar age, and τ is the duration of the heating. A specific form of H as a function of ρ and t is unimportant for our main conclusions. We do not specify the nature of the heat source (although we discuss possible models in Sect. 5). In the majority of calculations we set $\tau = 5 \times 10^4$ years to explain high observed thermal states of all selected SGRs and AXPs (Sect. 4). We vary H_0, ρ_1 and ρ_2 (and we vary additionally τ in some runs), in order to understand which rate, location and duration of heat release are consistent with observations and with the energy budget of an isolated neutron star.

To quantify the energy generation within the star, we introduce the total heat power W^∞ [erg s^{-1}], redshifted for a distant observer,

$$W^\infty(t) = \int \mathrm{d}V\, \mathrm{e}^{2\Phi} H, \tag{2}$$

where dV is the proper volume element; Φ is the metric function which determines gravitational redshift; and $H(\rho, t)$ is given by (1).

In the neutron star core we employ the equation of state of stellar matter proposed by Akmal et al. (1998) (their model Argonne V18 + δv + UIX*). This equation of state is currently thought to be the most elaborated equation of state of neutron-star matter. We use a convenient parameterization of this equation of state suggested by Heiselberg and Hjorth-Jensen (1999) and extended by Gusakov et al. (2005) (their version denoted as APR III). In this model, neutron star cores are composed of neutrons, protons, electrons, and muons. The maximum gravitational mass of stable neutron stars is $M = 1.929 M_\odot$. The powerful direct Urca process of neutrino emission (Lattimer et al. 1991) operates only in the inner cores of massive neutron stars with $M > 1.685 M_\odot$ (at densities $\rho > 1.275 \times 10^{15}$ g cm^{-3}).

We use neutron star models of two masses, $M = 1.4 M_\odot$ and $M = 1.9 M_\odot$. The $1.4 M_\odot$ model is an example of a neutron star with standard (not too strong) neutrino emission in the core; in a non-superfluid neutron star this neutrino emission is mainly produced by the modified Urca process. The circumferential radius of the $1.4 M_\odot$ star is $R = 12.27$ km, and the central density is $\rho_c = 9.280 \times 10^{14}$ g cm^{-3}. The $1.9 M_\odot$ model is an example of a neutron star with the neutrino emission greatly enhanced by the direct Urca process in the inner stellar core. For this star, $R = 10.95$ km, and $\rho_c = 2.050 \times 10^{15}$ g cm^{-3}.

4 Cooling calculations

Figure 1 shows the theoretical cooling curves $T_s^\infty(t)$ for the $1.4 M_\odot$ isolated magnetized neutron star without internal heating. The solid line is for a nonsuperfluid neutron star, and the dashed line SF is for a star with strong proton superfluidity in the core. This superfluidity greatly suppresses neutrino emission in the core which noticeably increases T_s^∞ at the neutrino cooling stage (e.g., Yakovlev and Pethick 2004). The surface temperature of these stars is highly nonuniform (the magnetic poles are much warmer than the equator); the figures show the average effective surface temperature (e.g., Potekhin et al. 2003).

The key problem is that the magnetars are much warmer than ordinary cooling neutron stars. The observations of ordinary neutron stars can be explained (within many different scenarios) by the cooling theory of neutron stars without additional heating sources (e.g., Yakovlev and Pethick 2004; Page et al. 2006). In contrast, the observations of magnetars imply that the magnetars have additional heating sources. We assume that these sources are located in the bulk of magnetars, at $\rho > \rho_b$. Note that there are alternative models which suggest that powerful energy sources operate in magnetar magnetospheres (Beloborodov and Thompson 2006).

Thus, to explain the observations of magnetars we have calculated a series of cooling models of neutron stars with $B = 5 \times 10^{14}$ G and internal heating sources given by (1). The results are presented in Figs. 2, 3, 4, 5 and 6. Our simulations with a powerful internal heating show that after a short initial relaxation ($t \lesssim 10$ years) the star reaches a quasi-stationary state. These states are governed by the heating source; the generated energy is mainly carried away by

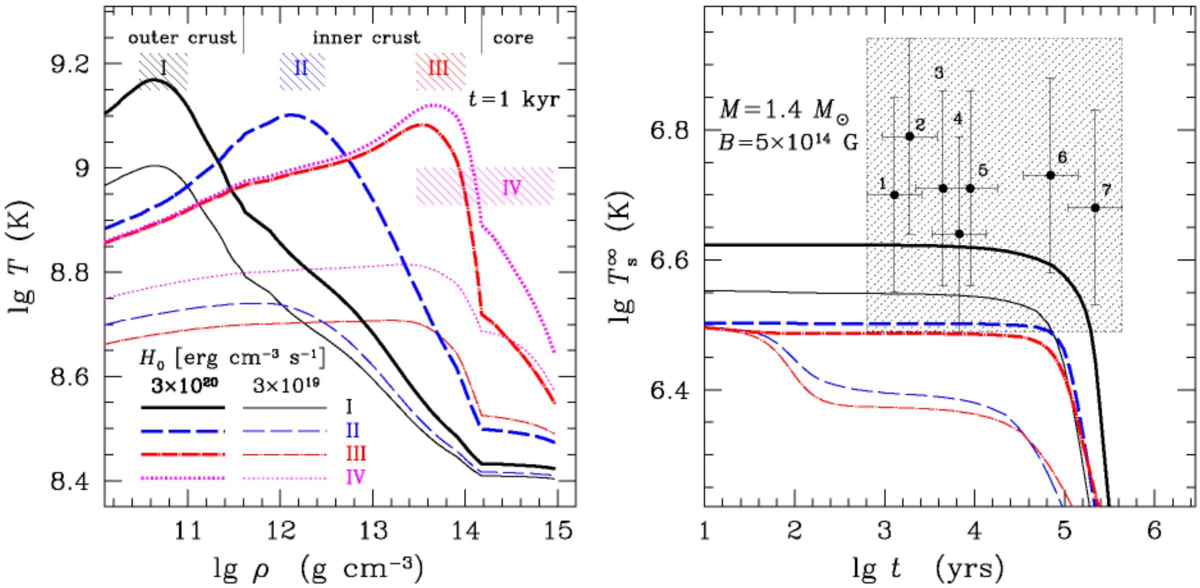

Fig. 2 *Left:* Temperature profiles within the neutron star of the mass $M = 1.4M_\odot$ and age $t = 1000$ years with four different positions *I–IV* of the heating layer (see text) shown by hatched rectangles and with two levels of the heating rate $H_0 = 3 \times 10^{19}$ and 3×10^{20} erg cm^{-3} s^{-1}(*thin* and *thick lines*, respectively). The magnetic field is $B = 5 \times 10^{14}$ G. *Right:* Cooling curves for the models with the heating layers *I–III* compared with the observations. From Kaminker et al. (2006)

neutrinos, although some fraction diffuses to the surface and radiates away by photons. The interior of these cooling neutron stars is essentially non-isothermal.

Our results are sufficiently insensitive to the neutron star mass, and we will mainly employ the neutron star model with $M = 1.4M_\odot$ (but present some results for the $1.9M_\odot$ star in Fig. 3). In addition, the results are not too sensitive to superfluidity in stellar interiors and we will mostly consider non-superfluid neutron stars. We assume the duration of the energy release $\tau = 5 \times 10^4$ years in all calculations excluding those presented in Fig. 4.

The left panel of Fig. 2 shows the temperature distributions inside the star with $M = 1.4M_\odot$ and $t = 1000$ years. The age $t = 1000$ years is taken as an example; the results are similar for all values of $t \lesssim \tau$. We have considered four locations of the heat layer, $\rho_1 - \rho_2$ (see (1)):

(I) 3×10^{10}–10^{11} g cm^{-3}(in the outer crust, just below the heat blanketing envelope)
(II) 10^{12}–3×10^{12} g cm^{-3}(at the top of the inner crust)
(III) 3×10^{13}–10^{14} g cm^{-3}(at the bottom of the inner crust) and
(IV) 3×10^{13}–9×10^{14} g cm^{-3}(at the bottom of the inner crust and in the entire core)

These locations are marked by hatched rectangles. We take two different heat rates, $H_0 = 3 \times 10^{19}$ and 3×10^{20} erg cm^{-3} s^{-1}, and the duration of the heat release $\tau = 5 \times 10^4$ yr.

As seen from the left panel of Fig. 2, the neutron star core is much colder than the crust because the core quickly cools down via neutrino emission (via the modified Urca process in our case). Placing the heat sources far from the surface does not allow us to maintain a high surface temperature. The heating layer can be hot, but the thermal energy is carried away by neutrinos and does not flow to the surface. For the deep heating layers (cases II, III, or IV), the heat rate $H_0 = 3 \times 10^{19}$ erg cm^{-3} s^{-1}is insufficient to warm the surface to the magnetar level. The higher rate 3×10^{20} erg cm^{-3} s^{-1}in these layers is more efficient but, nevertheless, it is much less efficient than in the layer I. For $H_0 = 3 \times 10^{20}$ erg cm^{-3} s^{-1}the heating of the crust bottom (case III) and the heating of the entire core (case IV) lead to the same surface temperature of the star. Therefore, the best way to warm the surface is to release the energy in the outer crust, close to the surface.

The right panel of Fig. 2 shows cooling curves of the stars with $M = 1.4M_\odot$ for the same models of the heating layer as in the left panel (without curves for the case IV; they are not presented to simplify the figure). The cooling curves of the star of age $t \lesssim \tau$ are almost horizontal. This indicates that the star is kept warm owing to the internal heating alone.

Figure 3 compares the thermal evolution of neutron stars with the two masses, $M = 1.4M_\odot$ and $M = 1.9M_\odot$. We consider the same three locations I–III of the heating layer and one heating rate $H_0 = 3 \times 10^{20}$ erg cm^{-3} s^{-1}. The thick lines correspond to the $1.4M_\odot$ star (they are the same as in the right panel of Fig. 2). The thin lines refer to the massive $1.9M_\odot$ star. Such a star has an extremely large neutrino luminosity produced by the direct Urca process operating in the inner core (Sect. 3). If the heating layer is

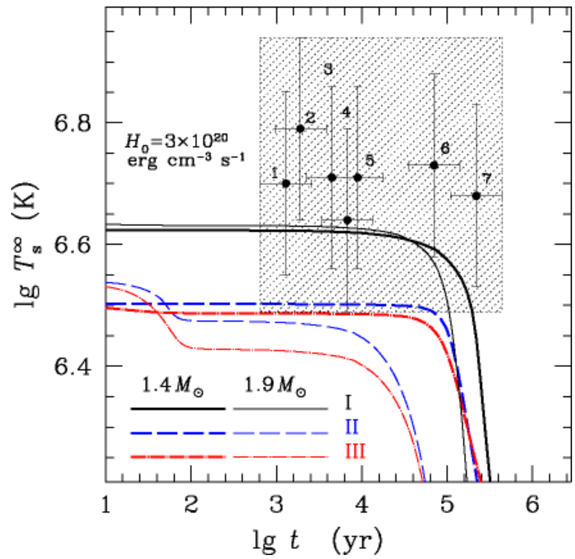

Fig. 3 Same as in the right panel of Fig. 2 for the three positions of the heating layer (*I–III*), one value of the heat rate and two neutron star masses, $1.4M_\odot$ (*thick lines*) and $1.9M_\odot$ (*thin lines*). From Kaminker et al. (2006)

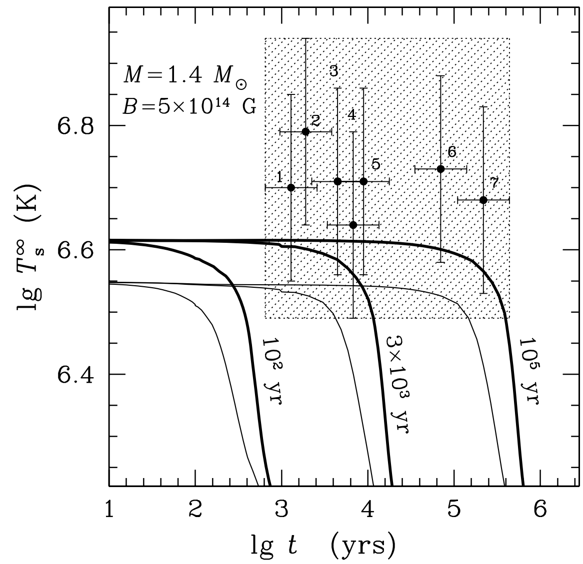

Fig. 4 Cooling curves of $1.4M_\odot$ neutron star with the heating layer in the outer crust (case I) for the two heating rates $H_0 = 3 \times 10^{19}$ erg cm^{-3} s^{-1}(*thin lines*) and 3×10^{20} erg cm^{-3} s^{-1}(*thick lines*) as in Fig. 2 but for three values of the heat-release duration, $\tau = 10^2$, 3×10^3, and 10^5 years

located in the inner crust (cases II and III), the enhanced neutrino emission of the massive star induces rapid neutrino cooling and noticeably decreases the surface temperature of the star. If, in contrast, the heating layer is located in the outer crust (case I), a strong neutrino emission from the core weakly affects the surface temperature. The surface temperature becomes nearly insensitive to the physics of the stellar core and the inner crust, in particular, to the neutrino emission processes and superfluidity of matter. This means that the surface layers are thermally decoupled from the inner crust and the core. The same happens in ordinary young and hot cooling stars, before their internal thermal relaxation is over (Lattimer et al. 1994; Gnedin et al. 2001). The thermal decoupling in magnetars justifies our consideration of non-superfluid neutron stars. Notice, however, that the effects of superfluidity can be crucial for the cooling of ordinary neutron stars; e.g., Yakovlev and Pethick (2004), Page et al. (2006).

Our results demonstrate that for explaining the observations of magnetars one should locate the heating source in the outer crust and assume the heating rate $H_0 \gtrsim 10^{20}$ erg cm^{-3} s^{-1}. According to (1), the heating rate decays exponentially at $t \gtrsim \tau$, and the surface temperature drops down in response. This means the end of the magnetar stage—the star transforms into an ordinary neutron star cooling predominantly via the surface photon emission (e.g., Potekhin et al. 2003).

Figure 4 demonstrates the dependence of the cooling curves on τ, the duration of the heating process. The heating source is located in the outer crust. Since our magnetar models are wholly supported by the heating, they become cool as soon as the heating is switched off. The models with a short heating stage, $\tau = 100$ and 3000 years, cannot explain all the sources from the "magnetar box", while the models with $\tau \gtrsim 10^4$–10^5 years can explain them. Longer τ would require too large energy, in contradiction with the energy budget of neutron stars (Sect. 5). Therefore, the value $\tau \sim 5 \times 10^4$ years accepted for the majority of our cooling models seems to be optimal.

Figure 5 illustrates the sensitivity of magnetar cooling to the values of the thermal conductivity in the inner neutron-star crust. We present temperature profiles in the star with $M = 1.4M_\odot$ at $t = 1000$ years and cooling curves of this star for the heating layer that is located in the outer crust (case I) and has the heating rate $H_0 = 3 \times 10^{20}$ erg cm^{-3} s^{-1}. The thick lines are the same as in Fig. 2; they are calculated using our standard cooling code, which includes only the electron thermal conductivity in the crust (Gnedin et al. 2001). However, the inner crust contains not only electrons and atomic nuclei, but also free neutrons. As a consequence, thermal energy can also be transported by free neutrons. This neutron transport can be efficient, especially if neutrons are superfluid. The effect may be similar to the well known effect in superfluid ^{4}He, where no temperature gradients can be created in laboratory experiments because these gradients are immediately smoothed out by convective flows (e.g., Tilley and Tilley 1990). To simulate such an effect we have artificially introduced the layer of high thermal conduction in the inner crust, at densities from 3×10^{12} g cm^{-3} to 10^{14} g cm^{-3}, where we amplified the thermal conductivity (arbitrarily, for illustration) by a factor

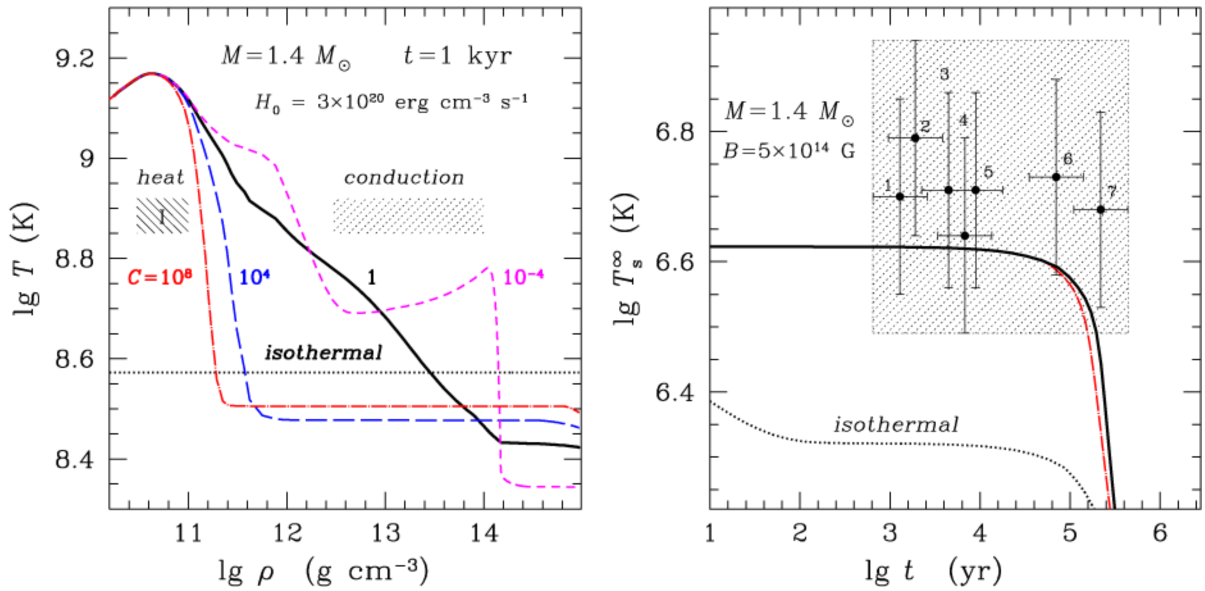

Fig. 5 The influence of thermal conduction in the inner crust on the thermal structure and evolution of the 1.4 $M_\odot$ magnetar with the heating layer in the outer crust (case I) and the heating rate $H_0 = 3 \times 10^{20}$ erg cm^{-3} s^{-1}. *Left:* The temperature profiles in the magnetar at $t = 1000$ years. The hatched rectangles show the positions of the heating layer and the layer, where the thermal conductivity was modified. *Right:* The cooling curves. The *thick solid lines* are the same as in Fig. 2. *Thinner long-dash*, *dot-and-dash*, and *short-dash* lines are for the star with the thermal conductivity modified by a factor of $C = 10^4$, 10^8, and 10^{-4}, respectively. The *dotted line* (marked *isothermal*) is for an infinite thermal conductivity at $\rho > 10^{10}$ g cm^{-3}. From Kaminker et al. (2006)

of $C = 10^4$ or 10^8. The amplification drastically changes the thermal structure of the inner crust, making it much cooler and almost isothermal. In addition, we have made a test run reducing artificially the thermal conductivity in the same layer by a factor of 10^4. This corresponds to $C = 10^{-4}$ and it mainly warms up the inner crust. Nevertheless, all these significant changes of the thermal state of the inner crust have almost no effect on the surface temperature and the cooling curves (which give another manifestation of the thermal decoupling of the outer crust from the inner stellar regions). Finally, we have simulated the neutron star cooling in the approximation of infinite thermal conductivity in the star bulk ($\rho > \rho_b = 10^{10}$ g cm^{-3}). Then the released heat is instantly spread over the star bulk and makes the stellar surface much cooler than in the case of finite conduction.

Figure 6 shows the integrated heating rate W^∞ given by (2) and the photon thermal surface luminosity of the star L_γ^∞ versus parameters of the heating layers. In the left panel we take three locations of the heating layer (I, II, III) and vary the heating rate H_0. One can see that only the heating of the layer I can produce $L_\gamma^\infty \gtrsim 3 \times 10^{35}$ erg s^{-1}, typical for magnetars. Moreover, the surface luminosity increases with H_0 much slower than W^∞. For $H_0 \gtrsim 10^{20}$ erg cm^{-3} s^{-1} and the layers II and III, the luminosity clearly saturates, so that pumping more energy into the heating layer does not affect L_γ^∞. The efficiency of converting the input heat into the surface photon emission ($L_\gamma^\infty / W^\infty$) is generally small. The highest efficiency is achieved if we warm up the outer crust (the layer I) at a low rate.

In the right panel of Fig. 6 we present L_γ^∞ and W^∞ as a function of the maximum density ρ_2 of the heating layer, for one value of the heating rate $H_0 = 10^{20}$ erg cm^{-3} s^{-1} and three fixed minimum densities of the heating layer ($\rho_1 = 3 \times 10^{10}$, 10^{12}, and 3×10^{13} g cm^{-3}). One can see the saturation of L_γ^∞ with growing ρ_2. If the heating layer extends into the stellar core, the integrated heating rate W^∞ is enormous, but this enormous energy is almost completely emitted by neutrinos.

Figure 6 compares theoretical values of L_γ^∞ with the thermal surface luminosities from the "magnetar box" (the lower shaded strip, estimated using the adopted values of T_s^∞ and the $1.4 M_\odot$ neutron star model). On the one hand, the heating should be intense to raise L_γ^∞ to the magnetar values. On the other hand, it is tacitly assumed that the energy W^∞ is persistently deposited into the heating layer during magnetar's life. As a consequence, the total deposited energy E_{tot} has to be restricted (cannot exceed the energy that can be stored in a neutron star). Let us assume further that the maximum energy of the internal heating is $E_{max} \sim 10^{50}$ erg. Then the maximum energy generation rate is $W_{max} \sim E_{max}/\tau \sim 3 \times 10^{37}$ erg s^{-1}, which is plotted by the upper horizontal solid line in Fig. 6. In this case the upper shaded space above this line is prohibited by the neutron-star energy budget.

A successful theory of magnetars as cooling neutron stars with internal heating has to satisfy two principal require-

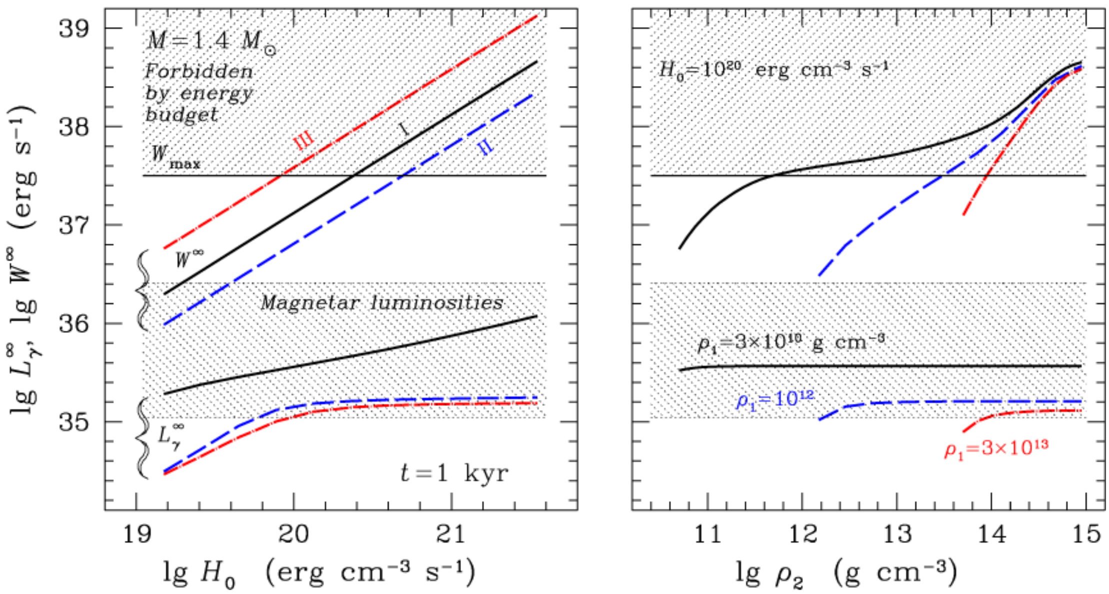

Fig. 6 The total heating power W^∞ (*higher curves*) and the surface photon luminosity L_γ^∞ (*lower curves*) versus parameters of the heating layer compared to the values of L_γ^∞ from the "magnetar box" (the *lower shaded strip*) and to the values of W^∞ forbidden by energy budget (the *upper shading*) for the neutron star with $M = 1.4M_\odot$ and $t = 1000$ years. *Left:* Three fixed positions of the heating layer of variable heating rate H_0. *Right:* Three fixed minimum densities ρ_1 of the heating layer, the fixed heating rate $H_0 = 10^{20}$ erg cm^{-3} s^{-1}, and variable maximum density ρ_2. From Kaminker et al. (2006)

ments. First, L_γ^∞ has to be sufficiently large to reach the "magnetar box"; and second, W^∞ has to be sufficiently low to avoid the prohibited region. These requirements can be reconciled for the heating source which is located in the outer stellar crust and has the heating rate H_0 between 3×10^{19} and 3×10^{20} erg cm^{-3} s^{-1}. A typical efficiency of heat conversion into the surface emission under these conditions is $L_\gamma^\infty / W^\infty \sim 10^{-2}$.

We have tested the sensitivity of our theoretical cooling curves to the level of neutrino emission in the magnetar core and crust. Variations of the neutrino emissivity in the inner crust and the core of a magnetar heated in the outer crust can strongly modify the internal thermal structure of the star but have almost no effect on the surface temperature and photon luminosity L_γ^∞. In contrast, L_γ^∞ is sensitive to the neutrino emission in the outer crust. In a warm outer crust, the neutrino emission is mainly produced by plasmon decay and electron-nucleus bremsstrahlung (see, e.g., Yakovlev et al. 2001). Very strong magnetic fields in magnetar crusts can greatly influence the plasmon decay process (which has not been studied in detail).

5 Discussion and conclusions

We have calculated the thermal structure and evolution of magnetars—SGRs and AXPs—in attempt to explain high surface temperatures and energy budget of these highly magnetized neutron stars. We have tried to present robust results independent of any specific theoretical model of the internal heating (available models are reviewed, e.g., by Woods and Thompson 2006 and Heyl 2006). We expect that our results place stringent constraints on possible models. Our main conclusions are:

(A) If the heating source is located inside the neutron star, it must be close to the surface, in the outer crust, at densities $\rho \lesssim 5 \times 10^{11}$ g cm^{-3}, and the heating rate should range from $\sim 3 \times 10^{19}$ to 3×10^{20} erg cm^{-3} s^{-1}. Were the heating source located deeper in the star, the heating energy would be radiated away by neutrinos, and it would be impossible to warm up the surface. This deeper heating would be very inefficient and would require more energy than a neutron star can have.

(B) Heating sources in the outer crust create a strongly heterogeneous temperature distribution within the neutron star. The temperature in the heating layer is higher than 10^9 K, but the deeper interior stays much colder. The thermal structure of the heating layer and the temperature of the magnetar surface are nearly insensitive to such physical parameters of the core and the inner crust as the equation of state, neutrino emission, thermal conductivity, superfluidity of baryons. This means thermal decoupling of the outer crust from the deeper layers. The total energy released in the heating layer during the magnetar lifetime ($\sim 10^4$–10^5 years) cannot be lower than 10^{49}–10^{50} erg; maximum 1% of this energy can be radiated by photons from the surface. This does not necessarily mean that the energy is stored in the outer crust—it must be converted into heat there.

Our results support the widely spread suggestion that the magnetars are not powered by their rotation, or by accretion, or by thermal energy accumulated in a cooling neutron star, or by strain energy accumulated in the crust. All these energy sources contain much less than 10^{49} erg required to explain the existence of the magnetars.

However, the necessary energy can be stored in the magnetic field if, for instance, the neutron star has a field $B \sim (1\text{–}3) \times 10^{16}$ G in its core. The Ohmic decay of this magnetic field can be accompanied by a strong energy release in the outer magnetar crust, where the electric conductivity is especially low and the Ohmic dissipation is strong. The magnetic field structure in the star can be much more complicated than magnetic dipole, which can further enhance the Ohmic dissipation in the outer crust. There could be other mechanisms of the magnetic energy release in the outer crust. For instance, rearrangements of the internal magnetic field in the course of the magnetar evolution can lead to the generation of waves (perturbations). These waves can propagate toward the stellar surface, decay in the outer crust and warm up this crust. Some mechanisms of wave generation are outlined by Thompson and Duncan (1996).

It is possible that the thermal radiation of magnetars is emitted from a smaller fraction of the magnetar surface, for instance, from hot spots around magnetic poles. Then the total heating energy could be lower. However, observed thermal X-ray luminosities of magnetars $\sim 10^{34}$–10^{36} erg s^{-1} (e.g., Mereghetti et al. 2002; Kaspi and Gavriil 2004; Woods and Thompson 2006) are in a reasonable agreement with the range of thermal luminosities in Fig. 6, which are calculated assuming the emission from the entire surface.

There is still no solid theory of the internal magnetar heating. Our basic results are that the heating energy released in magnetars must be at least two orders of magnitude higher than the photon thermal energy emitted through their surface, and the energy release should occur in the outer stellar crust. These conclusions are model-independent and stem from the well-known principle that hot stellar objects are strong sources of neutrino emission.

Also, let us point out alternative theories of magnetars, which assume (e.g., Beloborodov and Thompson 2006) that the main energy release takes place in the magnetar's magnetosphere, and the radiation spectrum is formed there (owing to comptonization and reprocession of the quasi-thermal spectrum).

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