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Heating Magnetar Surface from the Crust

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Abstract. We study thermal structure of magnetars as highly magnetized neutron stars with internal heat sources in the crust. We show that heat does not tend spread along the surface. Most economical heaters are those placed in the outer crust in the form of hot layers (hot spots) under certain parts of the surface. The required heat intensity is consistent with Ohmic dissipation of electric currents within the heater. This dissipation of the magnetic energy, that is transported to the heater during magnetar life, can power quasi-persistent emission of magnetars.

1. Statement of the Problem

Observations indicate (e.g., Mereghetti 2008) that magnetars, aside of their bursting activity, are sources of powerful quasi-persistent X-ray emission during $\sim 10^5$ years of their life. We adopt the standard assumption that magnetars are powered by the energy of strong magnetic fields stored in the bulk of the star. We assume further that this energy is transformed into heat in certain region (regions) of the neutron star crust. Some fraction of the heat flows to the surface and then into the magnetosphere (to transfer into non-thermal emission there). We investigate possible parameters of the heater which are needed to support observable quasi-persistent emission of magnetars.

We will simulate heat transfer within the magnetar with two cooling codes taking the $1.4\,M_\odot$ neutron star model with the nucleon core. We do not include the effects of nucleon superfluidity which are not very important for a given problem (Ho et al. 2012). In the core, we will use the equation of state of nucleon matter constructed by Akmal et al. (1998) (the same version that was used in Kaminker et al. 2006). The circumferential stellar radius of the star is $R = 12.27$ km, and its central density is $\rho_c = 9.280 \times 10^{14}$ g cm^{-3}. Recall that the maximum mass of neutron stars for this equation of state is $1.929\,M_\odot$, and the powerful direct Urca process of neutrino emission in the core becomes allowed at $M > 1.685\,M_\odot$. Therefore, our $M = 1.4\,M_\odot$ star without internal heat sources would cool slowly via modified Urca process of neutrino emission from the core. We employ the model of iron heat blanketing envelope (Kaminker et al. 2009) with the magnetic field $B = 5 \times 10^{14}$ G normal to the surface; the envelope is extended to the density $\rho_b = 10^{10}$ g cm^{-3}. The effects of magnetic field on neutrino emission in the blanketing envelope and in deeper regions of the crust are taken into account in the same way as reported previously by Kaminker et al. (2009).

We have used either our previous 1D fully relativistic cooling code (with spherically symmetric heat layer) or our new simplified 2D cooling code (with an azimuthally symmetric heater). The latter code simulates thermal evolution of the crust in a locally flat reference frame; the presence of the core is taken into account through the crust-core boundary condition with appropriate neutrino cooling function in the isothermal core. Specific magnetic field geometry and anisotropy of heat conduction under the heat blanket is disregarded (although in principle can be included). We have reached a good agreement of 1D and 2D results in cases where such agreement has been expected.

We have introduced the heater into the cooling code by specifying a phenomenological distribution of the heat power $H(\mathbf{r}, t)$ [erg cm^{-3} s^{-1}] in the crust. The radial distribution of the heat power has been taken following Kaminker et al. (2006):

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

where H_0 [erg cm^{-3} s^{-1}] is the initial ($t = 0$) heat intensity; $\Theta(\rho_1, \rho_2) \approx 1$ in some density range $\rho_1 \leq \rho \leq \rho_2$, and $\Theta(\rho_1, \rho_2) \approx 0$ outside this range (in calculations, the step-like function Θ has been smoothed out as shown in Fig. 1c); the exponent accounts for the decrease of the heat power with time; H_0, ρ_1, ρ_2, and τ are treated as free input parameters. In the 2D calculations, we have also assumed that Θ depends on the angle θ between $\mathbf{r}$ and the magnetic axis, so that the heater looks like a hot spot under the surface of some angular size θ_0.

Without the heater, our neutron star is insufficiently hot to explain the activity of magnetars. Including the heater, at $t \gtrsim 100$ yr the star reaches a quasi-stationary state which is solely powered by the heater and disappears at $t \gtrsim \tau$ when the heat intensity dies out. To be specific, we set $\tau = 5 \times 10^4$ yr and considered the case of $t \ll \tau$.

2. Results

We have performed a set of 2D calculations of quasi-stationary states of magnetars powered by a hot-spot heater. We have varied the position of the heater, its angular size θ_0, and the heat intensity. Surprisingly, the heat does not tend to spread along the surface, as illustrated by Figs. 1a and 1b. Similar conclusion has been made by Pons & Rea (2012) in modeling heat outflow in magnetar outbursts near magnetic poles with anisotropic heat conduction throughout the crust; such a conduction canalized the heat propagation in radial direction. In our calculations, the thermal conduction does not canalize the heat outside the blanketing envelope, but the result is the same. Thus the conduction mainly carries the generated heat inside and outside the star (and the heat can also be radiated away by neutrinos). The internal hot spot just projects onto the surface (Figs. 1a and 1b); the generated heat flows out of the star through the projected area. This heat transport can be accurately reproduced with the 1D code (Figs. 1c and 1d) that has been used further. Naturally, it allows us to consider any hot spot geometry. Note, however, that assuming a complicated magnetic field geometry (strong toroidal fields) and highly anisotropic heat conduction in the crust, one can obtain spreading of heat along the surface (Pons et al. 2009); we do not consider these cases.

We have varied positions and heat intensities H_0 of the heater (Figs. 1c and 1d) and observed two distinctly different regimes. The first, *heat conduction regime* is typically realized at $H_0 \lesssim 10^{20}$ erg cm^{-3} s^{-1}, in which case the temperature in the heater is

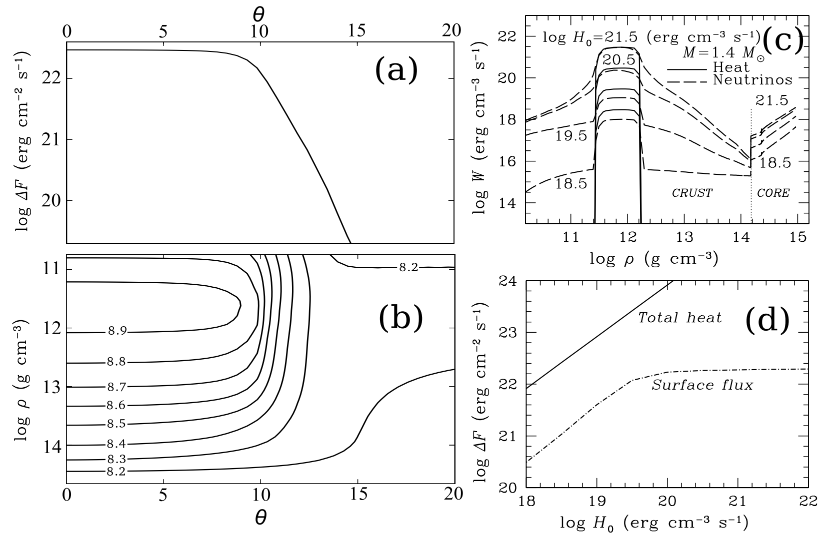

Figure 1. (a) Excess heat flux though the magnetar surface produced by the 2D heater ($\rho_1 = 3.2 \times 10^{11}$, $\rho_2 = 1.6 \times 10^{12}$ g cm^{-3}, $H_0 = 10^{19.5}$ erg cm^{-3} s^{-1}, $\theta_0 = 10°$, $t = 10^4$ yr) as a function of θ. (b) Lines of constant $\log T$ (numbers next to curves) within this magnetar versus θ and ρ. (c) Heat power (solid lines) and neutrino energy losses (dashes) versus density in the magnetar of age $t = 1$ kyr with spherical heat layer at the same ρ_1 and ρ_2 for four values of $\log H_0$. (d) The *total heat* power (divided by $4\pi R^2$, solid line) generated in the same magnetar, and associated extra heat flux ΔF conducted through the surface (dash-dots) versus H_0.

$T \lesssim 10^9$ K. The neutrino emission in the crust is then relatively unimportant. The warmest place in the star is naturally the heater itself; the maximum temperature occurs within a few meters from its outer boundary. The heat generated at this place flows to the surface and produces quasi-persistent emission of magnetars. The rest of the heat is transported by thermal conduction inside the star (and can be carried away by neutrinos from there). The maximum amount of the generated heat that travels to the surface is about a few per cent (Fig. 1d); this happens when the heater is placed in the outer crust. Moving the heater to the crust-core interface reduces this amount by a factor of 10.

The second, *neutrino emission regime* is typically realized at $H_0 \gtrsim 10^{20}$ erg cm^{-3} s^{-1} ($T \gtrsim 10^9$ K). The main fraction of the heat is then emitted by neutrinos in the heater vicinity (Fig. 1c), heat conduction being less important. With increasing H_0, the generated heat power grows up but the extra heat is carried away by neutrinos. The temperature in the heater becomes somewhat higher, but it is slightly changed outside the heater. The heat flux through the surface is almost insensitive of H_0 (Fig. 1d). It is the *maximum steady-state heat flux emitted from the surface of the neutron star that is heated from inside*; it is $\sim 10^{-3}$ of the Eddington heat flux. Similar results have been reported earlier (e.g., Kaminker et al. 2006; Pons & Rea 2012).

Since the internal magnetic energy of magnetars is restricted, the heaters should be economical (transmit maximum thermal energy through the surface). In this respect, it is profitable to: (i) place the heaters in the outer crust; (ii) make them warm but not overheated ($H_0 \lesssim 10^{20}$ erg cm^{-3} s^{-1}); (iii) allow them to be spots (not spherical layers) to reduce the total generated heat.

3. Heater's Nature

The required heat intensity $H_0 \sim 10^{20}$ erg cm^{-3} s^{-1} is consistent with Ohmic decay of electric currents j within the heater, $H \sim j^2/\sigma \sim c^2B^2/[\sigma h^2(4\pi)^2]$, where σ is the electric conductivity and h is characteristic length-scale of the Ohmic decay region. It is really important to place the heater in the outer crust and make it warm. Only then, at low densities and high temperatures, the conductivity σ is low (e.g., Potekhin et al. 1999) to produce rapid Ohmic dissipation. The thermal conductivity would then also be low which would help to trap the heat near the heater and support the high temperature there. This indicates that h is $\sim$ of the radial heater width. For instance, at $B \sim 10^{15}$ G, $\sigma \sim 10^{22}$ s^{-1} and $h \sim 30$ m, we have $H \sim 6 \times 10^{19}$ erg cm^{-3} s^{-1}.

It is reasonable to assume that the magnetic energy of the magnetar is stored in the bulk of the star, not near the heater. Then it has to be transported to the heater to power it for a long time. The nature of such transport is currently unclear. This transport could be variable which would produce observable variations of quasi-persistent emission of magnetars (e.g., Mereghetti 2008). Possible transport mechanisms could be: (i) Hall drift (or related instabilities; e.g., Rheinhardt & Geppert 2002; Viganò et al. 2012); (ii) thermomagnetic effects in the presence of large temperature gradients in the heater (e.g., Urpin et al. 1986); (iii) unexplored effects of hydrostatic structure and stability of the crust with account for magnetic forces.

All in all, the heater in the outer crust with $H_0 \sim 10^{20}$ erg cm^{-3} s^{-1}, of the width $\sim$ 30 m, and the radius R_{BB} that satisfies $(R_{BB}/R)^2 \sim 0.1$ would generate the total heat power $W \sim 5 \times 10^{35}$ erg s^{-1}. The heater efficiency could well be $L_s/W \sim 0.03$; then the quasi-persistent luminosity of the magnetar $L_s \sim 1.5 \times 10^{34}$ erg s^{-1}. Such values of L_s and R_{BB} are typical for magnetars (Mereghetti 2008). In that case the total energy, required for the magnetar activity during $\tau \sim 5 \times 10^4$ years, would be $W\tau \sim 2 \times 10^{46}$ erg, which could be the magnetic energy of the magnetar. The main problem in this scenario is to transport the magnetic energy to the heater.

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References

Akmal, A., Pandharipande, V. R., & Ravenhall, D. G. 1998, Phys.Rev.C, 58, 1804
Ho, W. C. G., Glampedakis, K., & Andersson, N. 2012, MNRAS, 422, 2632
Kaminker, A. D., Potekhin, A. Y., Yakovlev, D. G., & Chabrier, G. 2009, MNRAS, 395, 2257
Kaminker, A. D., Yakovlev, D. G., Potekhin, A. Y., Shibazaki, N., Shternin, P. S., & Gnedin, O. Y. 2006, MNRAS, 371, 477
Mereghetti, S. 2008, A&A Rev., 15, 225
Pons, J. A., Miralles, J. A., & Geppert, U. 2009, A&A, 496, 207
Pons, J. A., & Rea, N. 2012, ApJ, 750, L6
Potekhin, A. Y., Baiko, D. A., Haensel, P., & Yakovlev, D. G. 1999, A&A, 346, 345
Rheinhardt, M., & Geppert, U. 2002, Phys.Rev.Lett, 88, 101103
Urpin, V. A., Levshakov, S. A., & Iakovlev, D. G. 1986, MNRAS, 219, 703
Viganò, D., Pons, J. A., & Miralles, J. A. 2012, Comput. Phys. Comm. (doi:10.1016/j.cpc.2012.04.029)