MAGNETARS: INTERNAL HEATING AND ENERGY BUDGET*

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We develop models of magnetars as cooling neutron stars with an additional heating in a spherical internal layer. We show that in order to explain high observable thermal luminosities of magnetars and be consistent with the energy budget of neutron stars the heat source should be located in the outer neutron star crust and should have the heat intensity $\sim 3 \times 10^{20}$ erg cm^{-3} s^{-1}.

Magnetars form a special group of neutron stars[1] which contain soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs). They seem to be hot, isolated, slowly spinning neutron stars of age $t \lesssim 10^5$ yr with extremely strong magnetic fields, $B \gtrsim 10^{14}$ G. There is no strict theory of magnetar activity and evolution. Many theoretical models[1,2] are divergent and assume that magnetars are powered either by internal energy sources, or by magnetospheric processes, or by combination of both. We consider a possibility that magnetars are cooling neutron stars with internal heating (see Ref.[3] for details).

Cooling of magnetars has been simulated with our cooling code. The base of the neutron-star heat blanketing envelope, where the main temperature gradient is located in an ordinary cooling neutron star, was placed at a density of $\rho_\mathrm{b} = 10^{10}$ g cm^{-3} (a few hundred meters under the surface). The envelope was assumed to consist of iron and possess a strong dipole magnetic field which affects the thermal structure of the envelope. Neutrino emission from the blanketing envelope was neglected; the effects of the magnetic field (others than producing internal heating) in deeper layers were neglected as well. The cooling code calculates the thermal surface luminosity (or, equivalently, the effective surface temperature T_s^∞ properly averaged over a stellar surface and redshifted for a distant observer) as a function of the stellar age t. In Fig. 1 (from Ref.[3]) we compare the results with estimated values

*This research has been partially supported by the Russian Foundation for Basic Research (grants 05-02-16245, 05-02-22003), by the Federal Agency for Science and Innovations (grant NSh 9879.2006.2), by the Rikkyo University Invitee Research Associate Program, CNRS French-Russian program (grant PICS 3202), and by the Dynasty Foundation.

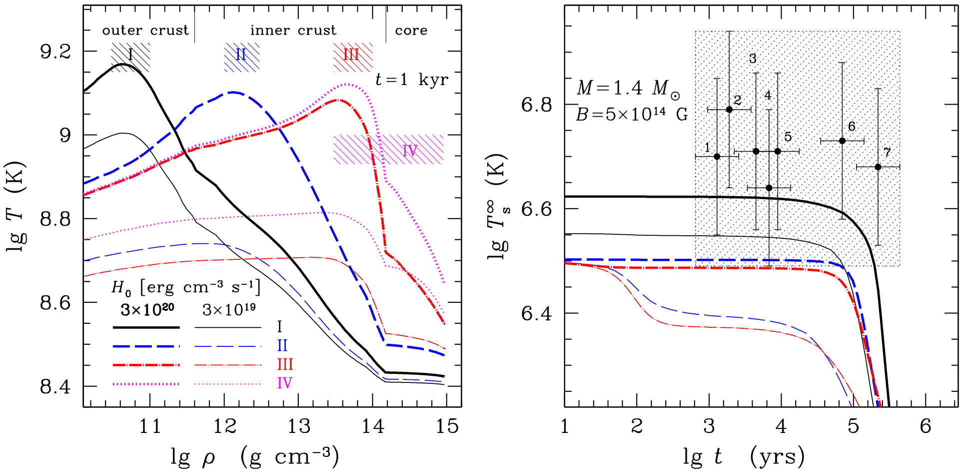

Fig. 1. Cooling of a nonsuperfluid $1.4\,M_\odot$ neutron star with a nucleon core and equation of state proposed in Ref.[4] The magnetic field in the heat blanketing envelope is dipole ($B = 5 \times 10^{14}$ G at the poles); the heating duration is $\tau = 5 \times 10^4$ years. *Left:* Temperature profiles within the star of age $t = 1000$ years with four different positions I–IV of the heating layer (indicated by hatched rectangles) and two levels of the heat intensity $H_0 = 3\times10^{19}$ (thin lines) and 3×10^{20} erg cm^{-3} s^{-1} (thick lines). *Right:* Cooling curves for these models compared with the observations. The shaded rectangle is the "magnetar box" to be explained by the theory.

of T_s^∞ for two SGRs (1=SGR 1900+14; 2=SGR 0526–66) and five AXPs (3=1E 1841–045;4=CXOU J010043.1–721134; 5=1RXS J170849–400910; 6=4U 0142+61; 7=1E 2259+586). The data are mostly taken from Ref.[1] and are highly uncertain.[3] If these values of T_s^∞ really refer to the surface radiation emergent from stellar interiors, magnetars are much hotter than ordinary cooling neutron stars of the same age.[5,6]

Calculations show that hot thermal states of magnetars can be explained, within our model, only by assuming an additional heat source which we suggest to operate in a spherical layer within the star. We have introduced this heating into the code in a phenomenological way. The heating rate H [erg cm^{-3} s^{-1}] (possibly associated with the magnetic field evolution) 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 heat intensity, $\Theta(\rho_1, \rho_2)$ is a step-like function ($\Theta \approx 1$ within some heating layer, $\rho_1 < \rho < \rho_2$; $\Theta \approx 0$ outside this layer), and τ is the heating duration. A specific form of H is not important for our main conclusions:

(1) We can construct heating layers consistent with the data, but with strongly restricted parameters. We obtain that hot magnetar states are solely supported by an additional heat. Once the heating source is switched off, the star quickly transforms into a much colder ordinary cooling neutron star. Accordingly, we must have $\tau \sim 10^4 - 10^5$ years. Shorter τ cannot explain older magnetars; longer τ would require too much heating energy.

(2) The heating layer should be located only in the outer magnetar crust ($\rho \lesssim 4 \times 10^{11}$ g cm^{-3}). Otherwise, even for a very high H_0 and a bulky heating layer (huge total integrated heat generation rate) the heat does not flow to the surface but, instead, is radiated by neutrinos from the stellar interior, leaving the surface much colder than necessary (Fig. 1). Even if the heat sources are placed in the outer crust, maximum ~1% of the heating energy is radiated by photons from the surface.

(3) The heat intensity in the outer crust should be $H_0 \sim 3 \times 10^{20}$ erg cm^{-3} s^{-1}. It makes magnetar interiors highly nonisothermal (Fig. 1), with $T \sim 2 \times 10^9$ K in the heating layer (contrary to ordinary cooling neutron stars). Lower H_0 is insufficient to heat the surface to the "magnetar box." Higher H_0 will not help to heat the surface (the heating layer will become too hot and the extra heat will be radiated away by neutrinos); in addition, one will need too much energy to support magnetar's activity during its life ($\gtrsim 10^{50}$ ergs, which a neutron star cannot afford).

(4) The heated outer magnetar crust is thermally decoupled from deeper interior and highly insensitive to the physics of the inner crust and the neutron star core (to the equation of state, composition of matter, neutrino emission mechanisms, superfluidity). This is in sharp contrast to ordinary cooling neutron stars whose thermal states strongly depend on the physics of internal layers.[5,6] On the other hand, thermal states of magnetars are very sensitive to the physics of outer crust[7] (first of all to neutrino emission there).

(5) In our scenario, magnetars differ from ordinary neutron stars by the presence of some (probably magnetic) internal energy ($\sim 10^{49} - 10^{50}$ erg). It can be stored in the whole magnetar body (e.g., $B \sim (1-3) \times 10^{16}$ G in the core) and released in the outer crust during $\tau \sim 10^4 - 10^5$ years. The storage and release mechanisms remain to be explored. The release may be transient, leading to observed transient activity of magnetars.

Our results should be further elaborated, particularly, by a careful treatment of neutrino emission and heat transport in a magnetic field in the whole outer crust.[7] However, our conclusions seem rather insensitive to details of calculations.[3,7] New observations and modeling will hopefully reveal the magnetar nature in near future.

DGY is grateful to the organizers of MG11 for financial support.

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