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Magnetic field dissipation in nucleonic neutron star cores

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Abstract. We study the long-term heating due to magnetic field decay in the core of neutron star. Two cases for the nucleonic core are considered: normal and strongly superconducting. We give simple scaling relations (depending on the internal stellar temperature and the averaged magnetic field in the core) to estimate the magnetic field decay rate for the most important dissipation processes. Comparison to properties of observed neutron stars suggests that heating due to the magnetic field decay is (at least partially) responsible for the thermal states of middle-aged magnetars and highly-magnetized isolated neutron stars with ages of 1 — 10 Myr.

Keywords. magnetohydrodynamics, stars: neutron, stars: magnetic fields

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Isolated neutron stars (NSs) are cooling by neutrino flux from their core and by photon emission from their surface, and heating by various internal sources, e.g. by the magnetic field $\boldsymbol{B}$ decay (see Potekhin *et al.* 2015, for a review). Here we focus on the $\boldsymbol{B}$ decay in the core. For the normal (i.e., non-superfluid) *npe* core the field dissipation rate $\dot{W}_B$ [erg/s] was calculated by Gusakov *et al.* (2017) using a quasistationary approach to the core magnetohydrodynamics (QMHD, Goldreich & Reisenegger 1992). Gusakov *et al.* (2020) extended this approach to the $npe\mu$ core with strongly paired nucleons, but corresponding $\dot{W}_B$ was not derived. In this work, we use the QMHD approach to derive $\dot{W}_B$ for the $npe\mu$ core. Our microphysics input is similar to Gusakov *et al.* (2017, 2020), but we use more modern BSk24 equation of state of the core matter by Pearson *et al.* (2018).

In the normal $npe\mu$ core the processes responsible for the $\boldsymbol{B}$ decay are the particle species friction off each other and non-equilibrium Urca reactions (we assume that only the modified Urca process operates). We estimate the $\boldsymbol{B}$ decay rate as $\dot{W}_B \approx -H_R - H_{np}$, where $H_R \sim 10^{24} B_{14}^4 T_8^6\,\mathrm{erg\,s^{-1}}$ and $H_{np} \sim 10^{30} B_{14}^4 T_8^{-2} \mathcal{L}_6^{-2}\,\mathrm{erg\,s^{-1}}$. Here $T_8 = T/(10^8\,\mathrm{K})$ is the core temperature (the NS core is isothermal due to extremely high heat conductivity, see e.g. Potekhin *et al.* 2015), $B_{14} = B/(10^{14}\,\mathrm{G})$, where B is the magnetic field averaged over the core volume, and $\mathcal{L}_6 = \mathcal{L}/(10^6\,\mathrm{cm})$, where $\mathcal{L}$ is a typical lengthscale of $\boldsymbol{B}$ spatial variation over the core. The term H_R estimates $\boldsymbol{B}$ dissipation due to non-equilibrium reactions, and H_{np} stands for the field decay due to *np* mutual friction. We find that *ne*, $n\mu$, *pe* and $p\mu$ scatterings contribute to $\dot{W}_B$ negligibly in almost all cases where the normal NS model is relevant.

In case of nucleon pairing in the core, we assume that protons form the type II superconductor. Thus $\boldsymbol{B}$ is confined within the flux tubes, and e, μ, and n scattering off the flux tubes join the dissipative processes list. However, our estimates indicate that the n–flux-tube friction is unimportant for $\dot{W}_B$, whether neutrons are superfluid or not. There are two phases of the $\boldsymbol{B}$ evolution in the superconducting NS core (see Gusakov *et al.* 2020). During the first one, $\boldsymbol{B}$ dissipates rapidly by $e\mu$ friction in fast fluid flows along the field lines, the corresponding rate is $\dot{W}_B \approx -H_{e\mu} \sim -10^{36} B_{14}^2 T_8^{-5/3} \mathcal{L}_6^{-2}\,\mathrm{erg\,s^{-1}}$. Passing this phase, the field should reconfigure to suppress these flows. Then the second phase launches, where the main dissipation process is the lepton–flux-tube (ℓf) friction with the rate $\dot{W}_B \approx -H_{\ell f} \sim -10^{29} B_{14} \mathcal{L}_6^{-2}$ erg s^{-1}. The first phase should typically finish quickly, so we use $H_{\ell f}$ to estimate the long-term magnetic heating of the superconducting NS core.

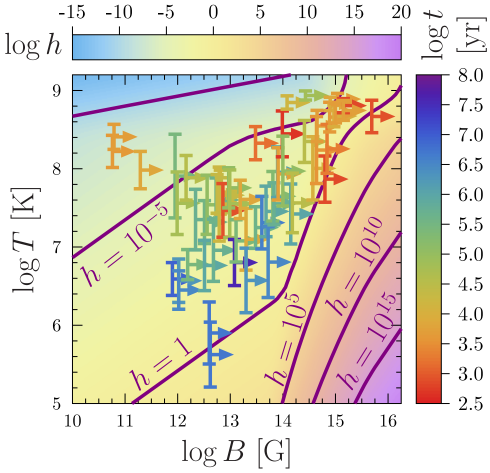

Figure 1. The heating ratio h as a function of the averaged internal field B and internal temperature T (pastel color map). Lines indicate constant h levels. The rainbow-colored bars are the observed NSs. See text for details.

The estimates for $\dot{W}_B$ given above are strictly valid for either the normal NS, or for strongly superconducting one. In an intermediate case (e.g, when $|\boldsymbol{B}|$ is much smaller than the second critical field) we use an artificial but representative interpolation between $\dot{W}_B = -H_R - H_{np}$ and $\dot{W}_B = -H_{\ell f}$. It is instructive to study $h = (-\dot{W}_B)/(L_\nu + L_\gamma)$, the ratio of the total heating power and total cooling luminosity. The neutrino luminosity L_ν is considered to be due to nn-bremsstrahlung (even partial p pairing suppresses the modified Urca ν emission, see Yakovlev *et al.* 2001). The photon luminosity L_γ is related to internal T by a heat blanketing envelope model (Beznogov *et al.* 2021). Notice that here we neglect possible non-isothermality of the NS crust due to the crustal $\boldsymbol{B}$ decay, see e.g. Potekhin *et al.* (2015). In fig. 1 we plot h via the pastel color map (solid lines for constant h levels; for certainty, we take $\mathcal{L} \sim 3$ km).

To compare our results to observations, we take observational data from Viganò *et al.* (2013) and Potehin *et al.* (2020) (with minor updates; we select only the NSs with two-sided estimates for L_γ, field at the pole B_p and age t). For each NS, we estimate the internal field as $B > B_p$, and derive a range of internal T from observed L_γ using eight models of the heat blanketing envelope (which differ by composition, surface temperature distribution model, and accounting for Coulomb plasma nonideality). Resulting positions of the observed NSs in the $B - T$ plane are shown in fig. 1 by rainbow-colored error bars (color for age t). Fig. 1 suggests that (almost) all observed NSs are located in the area $h < 1$. For a given T, the most magnetized NSs lie close to the line $h = 1$, where $\dot{W}_B + L_\nu + L_\gamma = 0$. It is especially pronounced for some of magnetars with $t \lesssim 10^4$ yr and old pulsars with $t \sim 10^6 - 10^7$ yr. This indicates importance of core heating for NS cooling studies.

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