Neutron Star Astrophysics at the Crossroads: Magnetars and the Multimessenger Revolution
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Heating from Electron Captures by Nuclei in Magnetar Crusts

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Abstract. The decay of the magnetic field in the interior of a magnetar may trigger electron captures by nuclei in the stellar crust, thus providing an internal source of heating. In turn, the onset of electron captures and the heat released are altered by the magnetic field due to the Landau–Rabi quantization of electron motion. The loss of magnetic pressure might also lead to pycnonuclear fusions of the lightest elements. The maximum amount of heat that can be possibly released by each reaction and their location are calculated using nuclear data from both experiments and theoretical predictions of the Brussels-Montreal models based on self-consistent Hartree-Fock-Bogoliubov calculations. Results are found to be consistent with those inferred empirically by comparing neutron-star cooling simulations with observed thermal luminosity of soft gamma-ray repeaters and anomalous X-ray pulsars.

Keywords. stars: neutron, stars: magnetic fields, nuclear reactions

1. Introduction

Magnetars are very active neutron stars exhibiting outbursts and giant flares revealing the existence of extreme magnetic fields exceeding 10^{14} G (see e.g. Esposito et al. 2021 for a recent review). These stars, observed as soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs), appear to be hotter than weakly magnetized neutron stars, thus requiring some internal heating source. Different mechanisms have been proposed, as critically reviewed by Beloborodov & Li (2016). A widely accepted explanation relies on the dissipation of mechanical energy during crustquakes (see, e.g., De Grandis et al. 2020). This mechanism is only effective deep enough beneath the stellar surface where matter is sufficiently cold to be in a solid state. On the other hand, heat sources should be located in the shallow region of the crust to avoid excessive neutrino losses, as shown by Kaminker et al. (2006) (see also Kaminker et al. 2009).

Cooper & Kaplan (2010) argued that the decay of the magnetic field in the crust of a magnetar may trigger exothermic nuclear reactions. Reasoning by analogy with accreting neutron stars, the compression of the stellar material resulting from the loss of magnetic pressure (rather than from the accumulation of material onto the stellar surface in accreting systems) increases the Fermi energy of the degenerate relativistic electron gas to the point that electron captures by nuclei become energetically allowed. With the increase of density, nuclei might also fuse although these pycnonuclear processes in cold dense matter remain very uncertain. In their analysis, Cooper & Kaplan (2010) assumed for simplicity that the same amount of heat is released and at similar locations in both (weakly magnetized) accreting neutron stars and in magnetars, although the conditions prevailing in the interior of these two classes of neutron stars are very different.

We have recently studied these processes taking into account the specificities of magnetars (Chamel et al. 2021), and examined whether the associated heating could explain the observed thermal luminosity of SGRs and AXPs.

2. Exothermic reactions in dense matter

Compression-induced electron captures. The compression of matter induced by the loss of magnetic pressure is very slow, recalling that the typical Ohmic dissipation time scale for the magnetic field is of the order of millions of years. We can therefore assume that a matter element containing nuclei (in their ground state) with proton number Z and mass number A evolves in quasiequilibrium until the pressure reaches the threshold P_β for the onset of electron captures. This process does not release any heat. However, the daughter nuclei (in some excited state) are generally unstable and undergo an exothermic electron capture. As nuclei sink deeper into the crust, further compression may give rise to delayed neutron emission, thus marking the transition to the inner crust (Chamel et al. 2015a; see also Chamel et al. 2015b for a discussion about the role of the magnetic field).

Threshold pressure and density. Assuming that the magnetic field is strong enough for electrons to be all confined to the lowest Landau–Rabi level, we have recently shown that the threshold pressure can be calculated analytically (Chamel et al. 2021):

$$\begin{aligned} P_\beta \approx\ & \frac{B_\star m_e c^2}{4\pi^2 \lambda_e^3}\left[\gamma_e^\beta \sqrt{(\gamma_e^\beta)^2-1} - \ln\left(\sqrt{(\gamma_e^\beta)^2-1}+\gamma_e^\beta\right)\right. \\ & \left. + \frac{C\alpha}{3}\left(\frac{4B_\star Z^2}{\pi^2}\right)^{1/3}\left((\gamma_e^\beta)^2-1\right)^{2/3}\right], \end{aligned} \tag{2.1}$$

where $B_\star$ is the magnetic field strength in units of the critical field $B_{\rm rel} = m_e^2 c^3/(e\hbar) \approx 4.41 \times 10^{13}$ G (e being the elementary electric charge, $\hbar$ the Planck-Dirac constant, m_e the electron mass and c the speed of light), $\lambda_e = \hbar/(m_e c)$ is the electron Compton wavelength, $\alpha = e^2/(\hbar c)$ is the fine-structure constant, C is a dimensionless constant characterizing the spatial arrangement of nuclei and for which we adopt the Wigner-Seitz value $C = -9/10(4\pi/3)^{1/3} \approx -1.4508$ (Salpeter 1954), and γ_e^β is the threshold Fermi energy in units of $m_e c^2$ given by

$$\gamma_e^\beta \equiv -\frac{Q_{\rm EC}}{m_e c^2} + 1\,. \tag{2.2}$$

Here $Q_{\rm EC}(A,Z) = M'(A,Z)c^2 - M'(A,Z-1)c^2 - E_{\rm ex}(A,Z-1)$ is the Q-value (in vacuum) associated with electron capture by nuclei (A,Z), where $M'(A,Z)$ is the nuclear mass (including the rest mass of Z protons, $A-Z$ neutrons, and Z electrons) and $E_{\rm ex}(A,Z-1)$ is the excitation energy of the daughter nuclei. The mean baryon number density at the onset of the first electron capture is given by (Chamel et al. 2021)

$$n_\beta \approx \frac{B_\star}{2\pi^2\lambda_e^3}\frac{A}{Z}\sqrt{(\gamma_e^\beta)^2-1}\,. \tag{2.3}$$

Heat released by electron captures. The maximum possible amount of heat per nucleus released by electron captures has been also determined analytically considering that the daughter nuclei of the second electron captures are in their ground state and ignoring the fraction of energy carried away by neutrinos (Chamel et al. 2021):

$$\begin{aligned}\mathcal{Q}^* &\approx 2M'(A,Z-1)c^2 - M'(A,Z)c^2 - M'(A,Z-2)c^2 + 2E_{\rm ex}(A,Z-1)\\ &-m_e c^2 C\alpha \left(\frac{B_\star}{2\pi^2}\right)^{1/3} ((\gamma_e^\beta)^2-1)^{1/6}\Big[Z^{5/3}+(Z-2)^{5/3}-2(Z-1)^{5/3}\Big]. \end{aligned} \quad (2.4)$$

The last term, which accounts for electron–ion and ion–ion interactions and which is proportional to α, is very small. The heat is therefore essentially independent of whether matter is solid or liquid. This also shows that the magnetic field has almost no impact on the heat. However, contrary to what Cooper & Kaplan (2010) assumed, the heat released in a magnetar differs from that in an accreting neutron star because the initial composition is not the same.

Numerical results. We have calculated P_β, n_β and $\mathcal{Q}^*$ using the crustal composition of Mutafchieva et al. (2019). Nuclear masses were taken from the 2016 Atomic Mass Evaluation (Wang et al. 2017) supplemented with the Hartree-Fock-Bogoliubov model HFB-24 of Goriely et al. (2013). Excitation energies were extracted from the Nuclear Data section of the International Atomic Energy Agency website following the Gamow–Teller selection rules. Full numerical results can be found in Chamel et al. (2021). The maximum possible amount of heat released by electron captures is $\sim 0.02-0.1$ MeV per nucleon. Pycnonuclear fusion reactions of light elements accreted onto the stellar surface from the fallback of supernova ejecta, from a disk or from the interstellar medium, could potentially deposit $\sim 1-2$ MeV per nucleon. All in all, the total amount of heat turns out to be of the same order of magnitude as that found in accreting neutron stars (Chamel et al. 2020). However, sources are found at higher densities, typically $10^{10}-10^{11}$ g cm^{-3} (corresponding to pressures $P_\beta \sim 10^{29}-10^{30}$ dyn cm^{-2}) for magnetic fields of order $10^{16}-10^{17}$ G. The errors of the analytical formulas (2.1), (2.3) and (2.4) are of order 10^{-3}%. Let us recall that these formulas are only valid in the strongly quantising regime.

3. Astrophysical implications

The range of densities where most of the heat from nuclear reactions is deposited corresponds to that determined empirically by comparing magnetar cooling simulations with thermal X-ray observations (Kaminker et al. 2006; see also Kaminker et al. 2009).

The time τ required for all the nuclei (A,Z) to capture electrons, roughly given by (Chamel et al. 2021)

$$\tau \sim \tau_B \frac{4\pi}{B^2}\Big[P_\beta(A,Z,B_\star) - P_{\rm min}(A,Z,B_\star)\Big] \quad (3.1)$$

($\tau_B \sim$ Myr being the characteristic time scale of magnetic field decay and $P_{\rm min}(A,Z,B_\star)$ the lowest pressure at which parent nuclei are initially present), is found to be of the same order in the different crustal layers, and more importantly of the same order as the kinematic age of magnetars (a few thousand years).

Finally, the heat power, estimated as (Chamel et al. 2021)

$$W^\infty \sim \frac{1}{\tau}\sum \mathcal{Q}^*(A,Z)\mathcal{N}(A,Z) \sim 10^{35}-10^{36}\ \text{erg/s}\,, \quad (3.2)$$

where $\mathcal{N}(A,Z)$ is the total number of nuclei (A,Z), is comparable to that found empirically by fitting theoretical cooling curves to observational data (Kaminker et al. 2006; see also Kaminker et al. 2009).

These simple estimates suggest that electron captures induced by the decay of the magnetic field may be a viable source of heating in magnetars. Unlike the more popular explanation involving crustquakes, the present mechanism does not require the crust to be solid. The decrease of centrifugal forces caused by the spin down of the star could also trigger nuclear reactions as studied in millisecond pulsars (Iida & Sato 1997). However, we have shown that this mechanism is only effective during the early days following the birth of the star (Chamel et al. 2021). For simplicity, we have focused on the most strongly magnetized neutron stars. The extension to less extreme magnetic fields is left for future studies. The detailed magnetothermal evolution of magnetars still requires full numerical simulations.

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