Thermal radiation of magnetars

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Thermal evolution of magnetars

Magnetars:
- **SXRs + AXPs** -- neutron stars with ultrahigh magnetic field: \( B \gtrsim 10^{14} \text{ G} \).
- Majority of data evidence -- they are powered neither by accretion nor by rotation
- Most probably -- they are driven by ultrahigh B-fields
- **Activity:** quasi-persistent thermal and non-thermal emission, X-ray and gamma-ray bursts, flares and giant flares, glitches, QPOs, etc.
- **Sources:** wild processes of magnetic energy release in neutron stars interiors or magnetospheres

Main problem:
- **SXRs + AXPs** are spending a lot of energy: up to \( W_{\text{tot}} \lesssim 10^{50} \text{ erg} \)
- Whether it could be the energy of ultrahigh B-field within the star (in the crust or core)

Main question:
- Where is this energy released and how? What are mechanisms?
Magnetars versus ordinary cooling neutron stars

Two assumptions:
1. The magnetar data reflect persistent thermal surface emission
2. Magnetars may be regarded as cooling neutron stars

There should be a HEATING!
Which we assume to be INTERNAL
Main trends: BB-temperatures vs. ages

Characteristic age: \( t_c = \frac{P}{2\dot{P}} \)

Inferred dipole magnetic field: \( B_d \approx 3.2 \times 10^{19} \sqrt{PP} \ G. \)

Olausen & Kaspi (2014)

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- **Magnetars**
- **High-B PSRs**
- **XINS**
- **RPPs**
Correlations: BB- temperatures vs. B-fields

Red symbols – young NSs ( < $10^4$ yr)

Blue squares – INSs with proton cyclotron spectral features

Pons et al. (2007)
Phenomenological approach

The aim is to explain thermal emission of magnetars

Basic assumption: internal heating is inherent feature of ultrahigh B-fields:

B-fields $\rightarrow$ heater $\rightarrow$ quasi-persistent thermal emission

Phenomenological points: the emission is powered by internal heat sources

- The maximum stored energy $E_{\text{tot}} \approx 10^{49} - 10^{50}$ erg can be the energy of internal magnetic field $B \approx (1-3) \times 10^{16}$ G in the magnetar internal crust and/or core

- The stored energy is released in the crust

This approach has been confirmed recently:

by series of 2D- calculations of magneto-thermal evolution:

Our approach is much more primitive, but it allows to set a few principal points which we believe to be useful.
Heating and cooling of neutron stars

Oversimplified equation of thermal diffusion with account of neutrino emissivity $Q_\nu$ and heating power per unit volume $H$:

\[
v T \frac{\partial T}{\partial t} = \text{div} (\kappa \nabla T) - Q_\nu + H
\]

(a) The thermal balance equation (GR)
(b) The heat transport equation (GR)

Surface photon luminosity:

\[
L_\gamma = 4\pi\sigma R^2 T_s^4
\]

Heat blanketing envelope

Including $Q_\nu$:

\[
T_s = T_s (T_b)
\]

$\rho_b = 10^{10} \text{ g cm}^{-3}$; thickness $\sim 100$ m; mass of the envelope $< 10^{-6} M_\odot$

Heat content of NS:

$U_T \sim 10^{48} T_9^2$ ergs

1D code:

\[
L_r (r) = 4\pi r^2 F_r (r, t),
\]

\[
T (r, t)
\]

2D code:

\[
F_{r, \theta} (r, \theta, t),
\]

\[
T (r, \theta, t)
\]
Features of internal heating

The energy can be stored in the entire star or in the inner crust but released in the outer crust

Local energy release (hot blob)

Energy release

Energy storage

Energy transport

Main problem
Phenomenological heater and calculations

Radial heat power distribution:

$$H(\rho, t) = H_0 \Theta(\rho_1, \rho_2) \exp(-t / \tau_0)$$

Four parameters: $\rho_1$, $\rho_2$, $H_0$, $\tau_0$

$\tau_0 = 5 \times 10^4$ yr

Angular heat power distribution:

Either hot “blob” – 2D code, 
then additional parameter $\theta_0$

Or hot spherical layer – 1D code

Total redshifted heat power:

$$W^\infty(t) = \int dV e^{2\Phi} H,$$

Run cooling code: in about ~ 10000 years quasi-stationary temperature distribution determined by the heat source.
Results of 2D code

Excess heat flux density: $\Delta F_L = F_L - F_{L0}$; $F_{L0}$ - heat flux without heater

H = \(10^{19.5}\) erg s\(^{-1}\) cm\(^{-3}\)

(A) 1.4 $M_\odot$

$\rho_1 \leq \rho \leq \rho_2$

$\Theta_0 = 10^\circ$

(B) 1.85 $M_\odot$

$\rho_1 = 3.2 \times 10^{11}$ g cm\(^{-3}\)

$\rho_2 = 1.6 \times 10^{12}$ g cm\(^{-3}\)

\[ \log_{10} T \]
Weak heat spreading along the surface

Heat does not spread along the surface: heater's area is projected on the surface. 1D and 2D codes give similar results.

Pons and Rea (2012)
But more general approach:
Pons, Miralles, Geppert (2009)
Vigano et al. (2013)

Carrying away pumped heat:

Thermal conduction to the surface (observable)

Neutrino emission (losses)

Thermal conduction inwards

Pumping heat

Heater
Temperature profiles inside $1.4 \, M_\odot$ and $1.85 \, M_\odot$ stars

1D - calculations

$$T^\infty(\rho) = T(\rho) \, e^{\Phi}$$

$$B = 10^{12} \, G$$

$$\rho_1 = 3.2 \times 10^{11} \, g \, cm^{-3}$$

$$\rho_2 = 1.6 \times 10^{12} \, g \, cm^{-3}$$

0 - $H_0 = 0$;

1 - $H_0 = 10^{18.5} \, erg \, s^{-1} \, cm^{-3}$

2 - $H_0 = 10^{19.5} \, erg \, s^{-1} \, cm^{-3}$

3 - $H_0 = 10^{20.5} \, erg \, s^{-1} \, cm^{-3}$

4 - $H_0 = 10^{21.5} \, erg \, s^{-1} \, cm^{-3}$
Total heat power vs. surface photon luminosity and heat flux towards NS core

Hot spot

\[ \Delta \Omega / 4\pi = 0.1 \]

“Eddington” limit:
Kaminker et al. 2006
Pons and Rea 2012

\[ W^\infty(t) = \int V e^{2\Phi} H, \]
Heating regimes

1. Conduction outflow regime:
   \[ T < 10^9 \text{ K}, \ H_0 < 10^{20} \text{ erg cm}^{-3} \text{ s}^{-1} \]

2. Neutrino outflow regime:
   \[ T > 10^9 \text{ K}, \ H_0 > 10^{20} \text{ erg cm}^{-3} \text{ s}^{-1} \]

Non-economical heater

What is observed as quasi-persistent emission is basically a small fraction of input energy

Most economical heater

- Position: Outer crust
- Heat power: \( H_0 < 10^{20} \text{ erg cm}^{-3} \text{ s}^{-1} \)
- Efficiency to heat surface: <3%
- Angular distribution: Hot spot
Nature of heating: Ohmic dissipation

**High temperature is needed:**
- Low electric conduction
- Low thermal conduction

**Similar matters:**
Aguilera, Pons, Miralles 2008
Pons, Miralles, Geppert 2009

**Heat rate :**

\[
H \sim \frac{j^2}{\sigma} \sim \frac{c^2 B^2}{\sigma h^2 (4\pi)^2}
\]

**Ohmic dissipation; electrical conductivity:**
For \( B \sim 10^{15} \text{ G}, \ \sigma \sim 10^{22} \text{ s}^{-1}, \ h \sim 30 \text{ m} \) \( \Rightarrow \ H \sim 6 \times 10^{19} \text{ erg cm}^{-3} \text{ s}^{-1} \)

**For \( \Delta \Omega/4\pi = (R_{BB}/2R)^2 \sim 0.1 \) \( \Rightarrow \ W_{\text{Ohmic}} \sim 10^{36} \text{ erg s}^{-1}, \)**

**Heat efficiency:** \( L_s/W_{\text{Ohmic}} \sim 1/30 \) \( \Rightarrow L_s \sim 3 \times 10^{34} \text{ erg s}^{-1} \)

**Total energy needed:** \( W_{\text{Ohmic}} \tau \sim 10^{47} - 10^{48} \text{ erg} \)

\( (\tau \sim 5 \times 10^4 \text{ yr}) \)
Main features of magnetars

- **Magnitars** -- **SGRs and AXP**s: neutron stars with *ultrahigh B-fields* -- exhibit strong persistent *thermal* and *non-thermal* emission.

- Magnetars may be treated as cooling neutron stars with *internal heating*.

- *Internal heating* is probably inherent feature of ultrahigh *B-fields*.

- The heating may be supported by *Ohmic decay*, e.g., inside local domains in the outer crust under *hot spots*.

- Mechanism of *B-field-energy* transport to the *heater* is not clear.
Main features of heating

- **Comparison of 2D and 1D calculations:**
  
  The heat *mainly* diffuses *radially* inwards → *neutrinos* from the NS core.
  
  Small fraction of the heat → outwards → thermal surface radiation

  *Heater is located in a blob → a hot spot radiates.*
  
  *Heater is distributed over a layer → the whole surface radiates."

- **Two regimes of heating:**

  (a) The *conduction outflow regime*:
  
  $$ H < 10^{2.0} \text{ erg cm}^{-3} \text{ s}^{-1}, \ T < 10^9 \text{ K}; $$
  
  The thermal emission is regulated by the heater’s power and the *neutrino* emission in the NS core;
  
  Strong thermal coupling:
  
  the outer crust with the core;

  (b) The *neutrino outflow regime*: $$ H > 10^{2.0} \text{ erg cm}^{-3} \text{ s}^{-1}, \ T > 10^9 \text{ K}; $$
  
  *Thermal decoupling*: the outer crust and the core.

The most economical heater is *intermediate*:

Efficiency of surface $T$–radiation $L/W$ does not exceed a few%.
Quiescent Luminosity vs. B-field

Inferred dipole B-field: \( B_d \approx 3.2 \times 10^{19} \sqrt{P \dot{P}} \text{ G} \)

Spin-down energy: \( \dot{E} = I \Omega \dot{\Omega} = - (2\pi)^2 I \dot{P} / P^3 \)

Characteristic age: \( t_c = P / 2 \dot{P} \)

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Olausen & Kaspi (2014)
Neutron star model

• EOS (APR IV): Akmal, Pandharipande, Ravenhall 1998, Heiselberg & Hjorth-Jensen 1999; neutrons, protons, electrons, and muons in NS cores

Maximum mass: \( M_{\text{MAX}} = 2.16 \, \text{M}_{\odot} \), \( R = 10.84 \, \text{km} \), central density = \( 2.45 \times 10^{15} \, \text{g/cc} \)

Example of slow cooling: \( M = 1.4 \, \text{M}_{\odot} \), \( R = 12.74 \, \text{km} \), central density = \( 7.755 \times 10^{14} \, \text{g/cc} \)

Direct Urca: central density > \( 1.05 \times 10^{15} \, \text{g/cc} \), \( M > 1.77 \, \text{M}_{\odot} \)

• Effects of superfluidity are neglected

• Iron heat blanketing envelopes (densities <\( 10^{10} \, \text{g/cc} \)), but role of light elements on the surface – Kaminker et al. 2009

• Radial magnetic field \( B = 5 \times 10^{14} \, \text{G} \) above hot spots: synchrotron neutrino emission in the crust + anisotropic thermal conductivity and neutrino emission in the blanketing envelopes

• Cooling codes: either 2D, or 1D
Neutrino emissivity $Q$ and heat intensity $H$ vs. density

Direct Urca kernel of high neutrino emission