Thermal emission of neutron stars with internal heaters

A.D. Kaminker

Ioffe Physical-Technical Institute, St. Petersburg, Russia

Coauthors: D.G. Yakovlev ¹, A.Y. Potekhin ¹, ²,

¹ Ioffe Physical-Technical Institute, St. Petersburg
² Central Astronomical Observatory at Pulkovo, St. Petersburg

and

A.A. Kaurov

The University of Chicago, USA

“Physics of Neutron Stars – 2014”, July 31, 2014
Specific features

• Kaminker et al. (2006, 2009) -- what’s the news?

• Comparison the results of 2D and 1D codes.
• Consideration **NSs** with typical field $B \approx 10^{12} \text{ G}$ in outer layers including a heat blaketing envelope.
• Detailed consideration of heat flux and neutrino emissivities
• Dependence on EOS of NS matter
Heating and cooling of neutron stars

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

$$c_v \frac{\partial T}{\partial t} = \text{div} (\kappa \nabla T) - Q_\nu + H$$

(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 $Q_\nu$:

$$T_s = T_s(T_b)$$

$\rho_b = 10^{10}$ 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: $F_{r, \theta}(r, \theta, t), T (r, \theta, t)$
**Phenomenological heater and calculations**

**Radial heat power distribution:**

\[ H(\rho, t) = H_0 \Theta(\rho_1, \rho_2) \exp\left(-t / \tau_0 \right) \]

Four parameters: \( \rho_1, \rho_2, H_0, \tau_0 \)

\( \tau_0 = 5 \times 10^4 \text{ yr} \)

\[ \rho_1 \leq \rho \leq \rho_2 \]

**Angular heat power distribution:**

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

Or hot spherical layer – 1D code

**Total redshifted heat power:**

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

Run cooling code: in about \( \sim 10000 \) years quasi-stationary temperature distribution determined by the heat source.
Two equations of state and model parameters

(1) Toy-model equation of state (EOS):

\[ \varepsilon = \varepsilon_0 \left( \frac{u - 2 - s}{1 + su} \right) + S u^\gamma (1 - 2x_p)^2. \]

- energy per baryon; \( \text{HHJ} (s, \gamma) \)

\[ u = \frac{n}{n_0}, \quad n_0 = 0.16 \text{ fm}, \quad \varepsilon_0 = 15.8 \text{ MeV}, \quad S_0 = 32 \text{ MeV}, \quad s \text{ and } \gamma \text{ - parameters.} \]

To fit the EOS by Akmal, Pandharipand & Ravenhall (1998) – (APR)

\[ s = 0.2, \quad \gamma = 0.6 \quad \text{HHJ (0.2, 0.6)} \]

This work: \( s = 0.1, \quad \gamma = 0.7 \quad \text{HHJ (0.1, 0.7)} \) in the NS core – \( M_{\text{max}} = 2.16 M_{\text{Sun}} \)

in combination with smooth composition \( \text{SC} \) in the NS crust: \( \text{SC} + \text{HHJ (0.1, 0.7)} \)

(2) Analytical parametrizations of the family BSk EOSs: Potekhin et al. (2013)

We use one representative of the BSk – family: BSk 21

by Goriely et al. (2010), Chamel et al. (2010), Pearson et al. (2011, 2012)

with maximum NS mass: \( M_{\text{max}} = 2.28 M_{\text{Sun}} \)
Equations of state and NS models

| Star model | $M/M_\odot$ | $R$ (km) | $\rho_{14}$ |
|------------|-------------|----------|--------------|
| HHJ        | 2.16        | 10.84    | 24.5         |
| BS\(k\)   | 2.28        | 11.07    | 22.9         |
| HHJ        | 1.85        | 12.32    | 11.34        |
| BS\(k\)   | 12.46       | 12.46    | 9.98         |
| HHJ        | 1.77        | 12.46    | 10.5         |
| BS\(k\)   | 1.57        | 12.58    | 8.09         |
| HHJ        | 1.4         | 12.74    | 7.78         |
| BS\(k\)   |             | 12.57    | 7.3          |
Excess heat flux density: \( \Delta F_L = F_L - F_{L0} \); \( F_{L0} \) is the heat flux without heater.
Results of 2D code as series of snapshots

Heater: angular distribution
\[ \theta_h \leq 10^\circ \]

Heater:
\[ \sim 400 \text{ m under surface} \]
\[ \sim 80 \text{ m width} \]

\[ \rho_1 = 3.2 \times 10^{11} \text{ g cm}^{-3} \]
\[ \rho_2 = 1.6 \times 10^{12} \text{ g cm}^{-3} \]
\[ H_0 = 10^{19.5} \text{ erg cm}^{-3} \text{ s}^{-1} \]
Heater: angular distribution

\[ \theta_h \leq 10^\circ \]
Heater: angular distribution

$\theta_h \leq 10^\circ$
Heater: angular distribution

\[ \theta_h \leq 10^\circ \]
Heater: angular distribution

$\theta \leq 10^\circ$
Weak heat spreading along the surface

Heater: angular distribution

$\theta_h \leq 10^\circ$

$\theta$
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 see:
Pons, Miralles, Geppert (2009)
Vigano et al. (2013)

Carrying away pumped heat:

Pumping heat

Neutrino emission (losses)

Thermal conduction to the surface (observable)

Thermal conduction inwards
Temperature profiles inside $1.4 \, M_{\text{Sun}}$ and $1.85 \, M_{\text{Sun}}$ stars

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

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

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

$0 - H_0 = 0; \quad \text{erg} \, \text{s}^{-1} \, \text{cm}^{-3}$

$1 - H_0 = 10 \quad 18.5$

$2 - H_0 = 10 \quad 19.5$

$3 - H_0 = 10 \quad 20.5$

$4 - H_0 = 10 \quad 21.5$
Neutrino emissivity and heat density profiles

(a) \[ \rho_1 = 3.20 \times 10^{10} \text{ g cm}^{-3} \]
\[ M = 1.4 \, M_{\text{Sun}} \]
\[ \rho_2 = 9.20 \times 10^{10} \text{ g cm}^{-3} \]
\[ M = 1.85 \, M_{\text{Sun}} \]

(b) \[ \rho_1 = 3.20 \times 10^{11} \text{ g cm}^{-3} \]
\[ \rho_2 = 1.60 \times 10^{12} \text{ g cm}^{-3} \]

(c) \[ \rho_1 = 3.20 \times 10^{12} \text{ g cm}^{-3} \]
\[ \rho_2 = 1.27 \times 10^{13} \text{ g cm}^{-3} \]
Total heat flux vs. surface photon luminosity and heat flux towards NS core

\( W^\infty \) – total redshift heat power,

Efficiency: \( \frac{L_s^\infty}{W^\infty} \sim \) a few %

\( L^\infty_{\nu\text{core}} \) – neutrino luminosity of the core

\( L_s^\infty \) – surface thermal luminosity
Heating regimes

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

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

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 |
Thermal relaxation of the neutron star crust

Energy storage in the crust of young NS is analogous to the hot layer heater: the neutrino outflow regime \( T \geq 10^9 \) K.

Thermal decoupling of NS crust and core at \( t < 10^{-100} \) years
Features of internal heating

The energy can be stored in the entire star or in inner crust but released in the outer crust.
Comparison of 2D and 1D calculations: the heat mainly diffuses radially inwards → neutinos 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 in a layer → the whole surface radiates.

Two regimes of heating:
(a) The conduction outflow regime: \( H < 10^{20} \text{ erg cm}^{-3} \text{ s}^{-1}, \ T < 10^9 \text{ K} \);
   The thermal emission is regulated by the heater’s power and the neutrino emission in the NS core;
   Strong thermal coupling: the outer crust ↔ the core;

(b) The neutrino outflow regime: \( H > 10^{20} \text{ erg cm}^{-3} \text{ s}^{-1}, \ T > 10^9 \text{ K} \);
   Thermal decoupling: the outer crust ↔ the core.

The most economical heater is intermediate: \( H \sim 10^{20} \text{ erg cm}^{-3} \text{ s}^{-1} \), it’s placed in the outer crust.
Efficiency of surface T-radiation \( L_s/ W \) does not exceed a few %.
Efficiency of the heater in more massive stars (with fast cooling) is higher.
Weak dependence results on EOS of NS matter.
Neutrino emission from NS core

**Nucleon composition:**
\[ N = n, p \]

**Direct Urca**
\[ n \rightarrow p + e + \bar{\nu}_e \quad p + e \rightarrow n + \nu_e \]

**Modified Urca**
\[ nN \rightarrow p\text{Ne}\bar{\nu} \quad p\text{Ne} \rightarrow nN\nu \]

**NN bremsstrahlung**
\[ N + N \rightarrow N + N + \nu + \bar{\nu} \]

**Amplified neutrino emission in the internal core of NS:**

**Neutrino emission from the entire stellar body:**

\[ Q_{\text{FAST}} = Q_{0F} T^6 \quad L_{\text{FAST}} = L_{0F} T^6 \]

\[ Q_{\text{SLOW}} = Q_{0S} T^8 \quad L_{\text{SLOW}} = L_{0S} T^8 \]
Total heat power vs. surface photon luminosity and heat flux towards NS core

"Eddington" limit:
Kaminker et al. 2006
Pons and Rea 2012
Toy-model: thermal radiation of magnetars

Hot spot under the surface is heated, e.g., by Ohmic dissipation.

Light elements in the outer envelopes increase efficiency of the thermal radiation. Kaminker et al. (2009)
Nature of heating: Ohmic dissipation

Ohmic dissipation heat rate

For $B \sim 10^{15}$ G, $\sigma \sim 10^{22}$ s$^{-1}$, $h \sim 30$ m $\Rightarrow H \sim 6 \times 10^{19}$ erg cm$^{-3}$ s$^{-1}$

For $(R_{BB}/R)^2 \sim 0.1$ $\Rightarrow W_{\text{OHMIC}} \sim 10^{36}$ erg s$^{-1}$, $L_s \sim 3 \times 10^{34}$ erg s$^{-1}$

HEAT EFFICIENCY: $L_s / W_{\text{OHMIC}} \sim 1/30$

TOTAL ENERGY NEEDED: $W_{\text{OHMIC}} \tau \sim 10^{44} - 10^{45}$ erg

($\tau \sim 5 \times 10^4$ yr)

Numerical example

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

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