THERMAL EVOLUTION OF ORDINARY NEUTRON STARS AND MAGNETARS

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• Introduction
• Thermal evolution of ordinary neutron stars
• Thermal evolution of magnetars
• Comparison of ordinary neutron stars and magnetars
• Conclusions

Rikkyo University, Tokyo, September 1, 2012
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HARD WORK ON MAGNETAR PHYSICS
Mystery: 
**EOS of superdense matter in the core**

For simplicity, consider nucleon core:
- neutrons
- protons
- electrons
- muons

EOS = ?
Superfluidity = ?
Ordinary neutron stars:
- Isolated neutron stars which cool by loosing their internal heat
- Middle-aged ($t < 1$ Myr)
- Show surface thermal radiation (mainly in X-rays)
Heat diffusion with neutrino and photon losses

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

Heat blanketing envelope: \[ T_s = T_s (T) \]

Heat content: \[ U_T \sim 10^{48} T_9^2 \text{ ergs} \]

Main cooling regulators:
1. EOS
2. Neutrino emission
3. Superfluidity
4. Magnetic fields
5. Light elements on the surface

Testing: Internal structure of neutron stars
Neutrino emission from cores of non-superfluid NSs

Outer core
Slow emission

Inner core
Fast emission

NS with nucleon core: 
N=n, p

Enhanced emission in inner cores of massive neutron stars:

Everywhere in neutron star cores:

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

\[
Q_{\text{SLOW}} = Q_{0S} T^8 \quad L_{\text{SLOW}} = L_{0S} T^8
\]
Neutrino emission of non-superfluid Neutron star

Casino da Urca – Urca – Durca – Murca – Kurca

Main neutrino mechanisms

Neutrino emission levels
THREE COOLING STAGES

<table>
<thead>
<tr>
<th>Stage</th>
<th>Duration</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relaxation</td>
<td>10—100 yr</td>
<td>Crust</td>
</tr>
<tr>
<td>Neutrino</td>
<td>10-100 kyr</td>
<td>Core, surface</td>
</tr>
<tr>
<td>Photon</td>
<td>Infinite</td>
<td>Surface, core, Reheating</td>
</tr>
</tbody>
</table>

Relaxation
Neutrino stage
Photon stage

 Isothermal interior

Stage $L_{\infty}$ ($K$)
Stage $T_{\infty}$ ($K$)

$\log t$ (yrs)
Gnedin et al. (2001)
<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Crab</td>
</tr>
<tr>
<td>2</td>
<td>PSR J0205+6449</td>
</tr>
<tr>
<td>3</td>
<td>PSR J1119-6127</td>
</tr>
<tr>
<td>4</td>
<td>RX J0822-43</td>
</tr>
<tr>
<td>5</td>
<td>1E 1207-52</td>
</tr>
<tr>
<td>6</td>
<td>PSR J1357-6429</td>
</tr>
<tr>
<td>7</td>
<td>RX J0007.0+7303</td>
</tr>
<tr>
<td>8</td>
<td>Vela</td>
</tr>
<tr>
<td>9</td>
<td>PSR B1706-44</td>
</tr>
<tr>
<td>10</td>
<td>PSR J0538+2817</td>
</tr>
<tr>
<td>11</td>
<td>PSR B2234+61</td>
</tr>
<tr>
<td>12</td>
<td>PSR 0656+14</td>
</tr>
<tr>
<td>13</td>
<td>Geminga</td>
</tr>
<tr>
<td>14</td>
<td>RX J1856.4-3754</td>
</tr>
<tr>
<td>15</td>
<td>PSR 1055-52</td>
</tr>
<tr>
<td>16</td>
<td>PSR J2043+2740</td>
</tr>
<tr>
<td>17</td>
<td>PSR J0720.4-3125</td>
</tr>
</tbody>
</table>

The graph shows a comparison of the cooling ages of neutron stars, with the cooling age $T_{\infty}$ plotted against the logarithm of time $t$. Each point on the graph corresponds to a different neutron star, with labels indicating their respective names and coordinates.
Interpretation of all observations of ordinary neutron stars

1=Crab
2=PSR J0205+6449
3=PSR J1119-6127
4=RX J0822-43
5=1E 1207-52
6=PSR J1357-6429
7=RX J0007.0+7303
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15=PSR 1055-52
16=PSR J2043+2740
17=PSR J0720.4-3125

Models of cooling neutron stars with different masses for two models of proton superfluidity

- **Observed middle-aged ordinary cooling NSs are mainly on neutrino cooling stage**
- **They cool from inside via neutrino emission; powered by internal thermal energy**
- **They have isothermal interiors = cores and surface are thermally coupled**
- **Good natural laboratories of superdense cores (neutrinos + superfluidity)**
- **They are just cooling; no extra heat sources required**
Thermal evolution of magnetars

Magnetars:
- AXPs + SXRs
- Neutron stars which are powered neither by accretion nor by rotation
- Possibly are powered by strong magnetic fields
- Activity: quasi-persistent thermal emission, flares and giant flares, QPOs
- Magnetospheric activity (twisted magnetospheres)

Main problem:
- Are spending a lot of energy
- Could be the energy of superstrong B-field within the star (in the core)

Main question:
- Where is this energy released and how?

Example: Supergiant flare of SGR 1806−20 on Dec. 27, 2004: $W_X \sim 10^{46}$ erg $\Rightarrow W_{\text{INPUT}} \sim 10^{50}$ erg
Magnetars versus ordinary cooling neutron stars
The need for heating: Luminosity representation

Two assumptions:
(1) The magnetar data reflect persistent thermal surface emission
(2) Magnetars are cooling neutron stars

There should be a HEATING!
Which we assume to be INTERNAL
Statement of the Problem

- To explain quasi-persistent thermal emission of magnetars
- Assume: the emission is powered by internal heat sources
- The maximum stored energy $E_{TOT}=10^{49} - 10^{50}$ erg can be the energy of internal magnetic field $B=(1-3)x10^{16}$ G in the magnetar core
- The stored energy is released in the crust
Neutron star model

- **EOS:** Akmal, Pandharipande, Ravenhall (APR III); neutrons, protons, electrons, and muons in NS cores
- **Direct Urca:** central density $> 1.275 \times 10^{15}$ g/cc, $M > 1.685 \, M_{\text{SUN}}$
- **Maximum mass:** $M_{\text{MAX}} = 1.929 \, M_{\text{SUN}}$
- **Example of slow cooling:** $M = 1.4 \, M_{\text{SUN}}$, $R = 12.27$ km, central density $= 9.280 \times 10^{14}$ g/cc
- **Effects of superfluidity are neglected**
- **Iron heat blanketing envelopes (densities <10^{10} g/cc)**
- **Radial magnetic field $B = 5 \times 10^{14}$ G above hot spots**
- **Cooling codes:** either 2D, or 1D
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 spot: 2D code

Or spherical layer: 1D code

Run cooling code: in about 100 years – quasi-stationary temperature distribution determined by the heat source
Results of 2D code

Heater: angles $\phi < 10^\circ$

Heater:
~400 m under surface
~80 m width

$$\rho_1 = 3.2 \times 10^{11} \text{ g cm}^{-3}$$
$$\rho_2 = 1.6 \times 10^{12} \text{ g cm}^{-3}$$
$$H_0 = 10^{19.5} \text{ erg cm}^{-3} \text{ s}^{-1}$$
Weak heat spreading along the surface

Heat does not want to spread along the surface:
Heater’s area is projected on the surface
1D and 2D codes give similar results

As in
Pons and Rea 2012
but see
Pons, Miralles, Geppert 2009

Carrying away pumped heat

Neutrino emission (waste)

Thermal conduction to the surface (useful)

Thermal conduction inside (waste)

Pumping heat
$H_0 = 0$

$\rho_1 = 3.2 \times 10^{11} \text{ g cm}^{-3}$
$\rho_2 = 1.6 \times 10^{12} \text{ g cm}^{-3}$

**Heat layer:**
- ~400 m under surface
- ~80 m width

**Age = 1000 yrs**
\[ H_0 = 10^{18.5} \text{ erg cm}^{-3} \text{ s}^{-1} \]
\( H_0 = 10^{19} \text{ erg cm}^{-3} \text{ s}^{-1} \)
\( H_0 = 10^{19.5} \text{ erg cm}^{-3} \text{ s}^{-1} \)
\[ H_0 = 10^{20} \ \text{erg cm}^{-3} \ \text{s}^{-1} \]
$H_0 = 10^{20.5} \text{ erg cm}^{-3} \text{ s}^{-1}$
$$H_0 = 10^{21.5} \text{ erg cm}^{-3} \text{ s}^{-1}$$
“Eddington” limit:
Kaminker et al. 2006
Pons and Rea 2012
\begin{align*}
\rho_1 &= 3.2 \times 10^{11} \text{ g cm}^{-3} \\
\rho_2 &= 1.6 \times 10^{12} \text{ g cm}^{-3} \\
W^\infty &= 2.6 \times 10^{23} \text{ erg cm}^{-2} \text{ s}^{-1} \\
H_0 &= 10^{19.5} \text{ erg cm}^{-3} \text{ s}^{-1}
\end{align*}
\[ \rho_1 = 1.0 \times 10^{12} \text{ g cm}^{-3} \]
\[ \rho_2 = 6.9 \times 10^{12} \text{ g cm}^{-3} \]
\[ \rho_1 = 3.2 \times 10^{12} \text{ g cm}^{-3} \]
\[ \rho_2 = 1.3 \times 10^{13} \text{ g cm}^{-3} \]
\[ \rho_1 = 1.0 \times 10^{13} \text{ g cm}^{-3} \]
\[ \rho_2 = 2.4 \times 10^{13} \text{ g cm}^{-3} \]
\[ \rho_1 = 3.2 \times 10^{13} \, \text{g cm}^{-3} \]
\[ \rho_2 = 5.6 \times 10^{13} \, \text{g cm}^{-3} \]
Moving heater towards core reduces efficiency
Kaminker et al. 2006
Pons and Rea 2006
TWO THERMAL REGIMES

\[ C \frac{\partial T}{\partial t} = \text{div} (\kappa \nabla T) - Q_v + H \]

I. Conduction regime
- Thermal relaxation
- Thermal coupling

II. Neutrino regime
- Thermal non-equilibrium
- Thermal decoupling

\( \log T \) vs \( \log \rho \) graph:
- Outer crust
- Inner crust
- Outer core
- Inner core
HEATING REGIMES

1

\[ T < 10^9 \text{ K}, \quad H_0 < 10^{20} \text{ erg cm}^{-3} \text{ s}^{-1} \]

Regulated by thermal conduction

2

\[ T > 10^9 \text{ K}, \quad H_0 > 10^{20} \text{ erg cm}^{-3} \text{ s}^{-1} \]

Regulated by neutrino emission

BASICALLY 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
Most economical model of magnetars

Magnetic spots under surface heated by Ohmic dissipation

$H_0 = 10^{20}$ erg cm$^{-3}$ s$^{-1}$

$M = 1.4 \ M_\odot$

$B = 10^{15}$ G
$B = 10^{14}$ G

$(R_{BB}/R)^2 = 0.1$

$H_0 = 10^{19}$

$B = 10^{15}$ G
$B = 10^{14}$ G
The energy can be stored in the entire star or in inner crust but released in the outer crust?
**Nature of heating: Ohmic dissipation**

**Numerical example**

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

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

**Ohmic dissipation heat rate**

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

**HEAT EFFICIENCY:** \( L_s / W_{\text{OHMIC}} \sim 1/30 \)

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

\( (\tau \sim 5 \times 10^4 \text{ yr}) \)
Mechanism: Unknown

Possibilities:

- Hall drift (and instability), e.g. Geppert and Rheinhardt (2002), Aguilera et al. (2008), Pons and Geppert (2010), Price et al. (2012)

- Thermomagnetic effects (thermopower) at large temperature gradients

- Instability (e.g., loss of mechanical stability due to magnetic forces); emission of hydromagnetic waves, etc.
Main features of magnetars

- Magnetars may be cooling neutron stars with internal heating.
- It is economical to place heat sources in the outer crust.
- The heat rate in the outer crust can be $H \sim 10^{20}$ erg s$^{-1}$ cm$^{-3}$, the total heat rate exceeding the thermal surface luminosity with a factor of $\geq 30$.
- The outer crust is thermally decoupled from deeper interior; the thermal radiation tests the physics of the outer crust.
- The heating may be supported by Ohmic decay under hot spots.
- Mechanism of magnetic field deposition to the heater is not clear.
### Ordinary cooling neutron stars versus magnetars

<table>
<thead>
<tr>
<th>Objects</th>
<th>Ordinary stars</th>
<th>Magnetars</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Interiors</strong></td>
<td>Isothermal</td>
<td>Non-isothermal</td>
</tr>
<tr>
<td><strong>Powered by</strong></td>
<td>Thermal energy of core</td>
<td>Heat sources in crust</td>
</tr>
<tr>
<td><strong>Thermal coupling</strong></td>
<td>Surface and core</td>
<td>Surface and heater</td>
</tr>
<tr>
<td><strong>Natural laboratories of</strong></td>
<td>Superdense core</td>
<td>Heater</td>
</tr>
<tr>
<td><strong>Allow to study of</strong></td>
<td>Neutrino emission and superfluidity in core</td>
<td>Energy release in heater (Ohmic dissipation?)</td>
</tr>
</tbody>
</table>