Thermal Evolution of Neutron Stars – past, current and future

Sachiko Tsuruta
Montana State University

Kyoto Conference, Kiken, February 2017
I. Historical Background

In the early to mid-1930s: Oppenheimer and Volkopf’s theoretical prediction of the existence of neutron stars; and Baade and Zwicky predicted that a supernova explosion will leave behind a compact neutron star.

In the late 1950s: J.A. Wheeler’s group calculated the structure of white dwarfs and neutron stars for the ideal Fermi gas (i.e., no nuclear interaction); A.G.W. Cameron, etc., included the nuclear force in the calculations of neutron star structure.
In the early 1960s: Giacconi et al. discovered Sco X-1, by a Rocket. Several theorists (Hayakawa, Chiu and Salpeter, etc.) suggested it may be a neutron star, but with various reasons soon rejected (e.g., the spectrum not blackbody, etc.), though much later observations showed it is a neutron star in a binary system; Friedman et al, from lunar occultation of the Crab nebula, showed that its X-ray source is extended.

Fig. 1: Sco X-1 - 1st X-ray source, - a NS in a binary

Fig. 2: Crab X-Ray source, with a pulsar
In ~ 1963-1966, ST and Cameron were interested in if a neutron star (NS) is hot enough to be observable. Their cooling calculations showed that, in principle, it could be observable, but probably the surface radiation is not as strong as Sco X-1 luminosity. (See Fig. 3),

In 1966, Bahcall and Wolf suggested that if a neutron star’s core includes pions it will cool too fast, and not observable – Bahcall suggested to ST to bet on the observability of NSs, ST declined.
Fig. 3: First NS cooling results – ST 1966, ST and Cameron 1966
• 1967: J. Bell, etc., discovered the first radio pulsar; Gold and Pacini suggested it is a rotating, magnetic neutron star. This interpretation is now universally accepted.

• Fig. 4.
1970: Launch of UHURU, the first X-ray satellite, observed many X-ray sources.

- In the 1980s: The launch of Einstein and then ROSAT X-ray source discoveries, with the X-ray telescopes – first the observation of the upper limits and then detections of NS temperatures – These detections supported the NS cooling calculations, first by ST and Cameron in the 1960s, and then many more. (See Figure 5).

- 1998: Launch of Chandra (July) and XMM/Newton (December) X-ray Satellites – Many more detections of neutron star temperatures, among many other discoveries, including X-ray pulsars, NSs in binary X-ray sources (e.g. Fig. 1), etc.
Fig. 5: Summary of Earlier Days: Proceedings of NS Conference (SENSE), Kyoto, 1990
I am glad that now the National Science Foundation and the Japan Society for the Promotion of Science accepted the proposal of this symposium as the first priority of a US-Japan Joint Seminar. I hope this symposium will be a milestone in neutron star physics.

In response to a request by Professor Tamagaki, I would like to present a cartoon version of the history of our study of the neutron star. I have classified the history into three eras.

First, as indicated in Fig. 1, the 1940s to the mid-1960s was the era of the prophet. Since Baade and Zwicky, we can identify several prophets, including those who are present at this banquet: Hayakawa, Tsuruta, Pines, Ruderman, and others. They predicted that the neutron star would have a strong bearing on nuclear physics, condensed matter physics, and gravitation.

The second is the era of believers and discoverers, indicated in Fig. 2. Needless to say, the discovery of pulsars provided a challenging hypothesis on the real existence of the neutron star. Then discovery of X-ray stars, X-ray bursts and X-ray pulsars confirmed that the neutron star is its major source. The Crab Nebula has been an excellent target of observation to study the neutron star itself and the interaction between the neutron star and its surrounding plasma.

Since the 1980s, as indicated in Fig. 3, the neutron star has been the place to study various disciplines of physics. There have been so many symposia and meetings on the neutron star that I can’t count them. I recall that in 1983 Professors Hoshi, Nakajima, and myself organized a symposium as part of the activities of the Institute of Solid State Physics, in which Professor Tamagaki played an important role. But then our understanding of the neutron star was still immature.
Fig. 7: Group photo of SENSE Conference
II Structure and Properties of Neutron Stars (NS) - Summary:

Typical stellar mass:  
\[ M \sim 1 - 2 \, M_\odot, \]

Typical stellar radius:  
\[ R \sim 8 - 16 \, \text{km} \]

Typical central density  
\[ \rho_c \sim 10^{17} - 18 \, \text{kg/m}^3 \]
\[ \sim 1 \text{ billion ton per teaspoon}!!! \]

Typical surface temperature (to be observable):  
\[ T_s \sim 10^5 - 6 \, \text{K}, \]

Typical magnetic field  
Strength of a pulsar  
\[ B \sim 10^{12} \, \text{gauss} \]
Maximum Mass of Neutron Stars:

Like a white dwarf, a neutron star has an upper limit on its mass: $\sim M_n(\text{max}) \sim 1 - 3 M_\odot$

Note: If no nuclear force, $M_{\text{max}} \sim 0.7 M_\odot$.

Note:

• The pressure within a neutron star comes from two sources
• One is the degenerate nature of the neutrons, and the other is the strong nuclear force that acts between the neutrons (and protons) themselves

Fermi energy $\gg$ thermal energy ($\sim kT$), within a neutron star. So, “Neutron degenerate pressure” is balanced with gravity (due to “Pauli Exclusion Principle” for neutrons)

→ neutron degenerate pressure supports the star!

See class notes for further details.
Detailed internal structure depends on the nuclear models – strong interaction among particles.

Outer crust I: ordinary heavy nuclei + e⁻

Outer crust II: n-rich heavy nuclei + e⁻

Inner crust:

n-rich heavy nuclei + free e⁻ + free n

Internal structure depends on the nuclear models – strong interaction among particles.
### (iii-c) EOS - Equation of Neutron Stars: Compactness: *Interactions between nucleons*

**Potential Energy V for a system (eV)**

<table>
<thead>
<tr>
<th>Strong Interaction</th>
<th>Model (A)</th>
<th>Model (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(+) : Repulsive Force</td>
<td>-</td>
<td>(+)</td>
</tr>
<tr>
<td>(-) : Attractive Force</td>
<td>(+)</td>
<td>(-)</td>
</tr>
</tbody>
</table>

**Table III-1: Properties of NS - Model dependent!**

<table>
<thead>
<tr>
<th>Model</th>
<th>(A)</th>
<th>(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ρ(center) tons/cm³</td>
<td>3 ~ 50</td>
<td>0.2 ~ 7</td>
</tr>
<tr>
<td>Mass/M☉</td>
<td>0.2~1.4</td>
<td>0.2~1.7</td>
</tr>
<tr>
<td>Radius (km)</td>
<td>7 ~ 20</td>
<td>15 ~30</td>
</tr>
</tbody>
</table>

See class notes for details.
Mass-Central Density Relation of Dense Stars

Fig. 4: Mass-central density relation of neutron stars and white dwarfs depends on “nuclear force”

Compactness (M/R) depends on “nuclear force”

- **Model (A)**
  - White Dwarf: Stable
  - Neutron Star: Stable

- **Model (B)**
  - White Dwarf: Stable
  - Neutron Star: Unstable!

**Graph Details**
- Logarithm of central density ($\log(\rho_c)$) vs. mass ($M/M_\odot$)
- Mass values: 1.4 $M_\odot$
(iii-e) Superfluidity and Superconductivity

A neutron star consists of a superfluid and superconducting core surrounded by a superfluid mantle and a thin, brittle crust.

Superfluidity of neutrons and superconductivity of protons are among the strange properties of neutron stars.

Note: Superfluid particles have no resistance, move freely. - important for cooling of neutron stars – come back later.

Summary

- For $\rho < \sim 10^{12} \text{ kg/m}^3$, “e-degenerate pressure” (White Dwarf)

- For $\rho > \sim 10^{17} \text{ kg/m}^3$, “n-degenerate pressure” (Neutron Star)

To oppose huge gravity, what if density $\rho > 10^{19} \text{ kg/m}^3$?  
$\rightarrow$ “nothing can support stars!”
$\rightarrow$ Black Hole (BH)!
II Thermal (Temperature) Evolution Model of Neutron Star compared with observation data

Comment: Are neutron stars (NS) cold? Not really – observable NS is about a million degrees on the surface (emit X-rays), so, in fact, very hot compared with ordinary stars. But density so large that Fermi energy still $\gg$ thermal energy, and hence the zero-temperature limit still applies.

Energy balance equation:
The temperature of neutron stars (NS) decreases in time due to neutrino loss first and then photon radiation!

$$-\frac{dE}{dt} = -C_V \frac{dT}{dt} = L_\nu + L_\gamma - H$$

where: $E$ = internal energy of NS; $T$ = internal temperature of NS; $H$ = time rate of heat generation inside NS; $C_V$ = specific heat capacity; $L_\nu$ = energy/time for emitted “neutrinos”; $L_\gamma$ = energy/time for emitted “photons”, $t$ = age of NS.
First Measurement of NS Temperatures by ROSAT, and Cooling Model of NS: ST 1986; Nomoto and ST 1987

Solid : Hot, Standard cooling
\[ n+N \rightarrow p+N+e^-+\nu, \]
\[ p+N+e^- \rightarrow n+N+\nu \]
\[ M \sim 1.2 \, M_\odot \]
with superfluid
\((N = n \, \text{or} \, p)\)

Dashed : Cool,
Non-Standard Cooling,
Extotic Particles
(Pion-cooling)
\[ M \sim 1.4 \, M_\odot \]
with superfluid

Obs. Data
a: Cas A point source
b: Crab pulsar
1: pulsar PSR J0822
2: Vela pulsar
4: Geminga pulsar
6: Pulsar PSR B1055

More Recent Results (*1):

**Input Physics:**

**Neutrino Processes**

**Standard Cooling:** modified URCA, plasmon, nucleon bremsstrahlung, etc., neutrino emissivity tc.

**Non-standard Cooling:** faster cooling, with ‘exotic’ processes such as direct URCA processes involving nucleons, pions, hyperons, kaons, quarks, etc., including pairing effects

**Note:** All non-standard cooling - too fast to be consistent with some observational detection data of e.g. Vela pulsar, without superfluid suppression

T72 constructed by Takatsuka (1972) [40], AO constructed by Amundsen and Østgard (1985) [41], and HGR constructed by Hoffberg et al. (1970) [42], respectively. The other models, NPC, ETA, E1 and E2 were constructed by Takatsuka and Tanaga (1980)(1982) [37].

The major effect of superfluidity on cooling is that when the interior temperature $T$ becomes below $T_{cr}$, all neutrino processes involving the superfluid particles decrease roughly as:

$$L_{\nu}(\text{super}) = L_{\nu}(\text{normal})R(T/T_{cr}),$$

where $L_{\nu}(\text{super})$ and $L_{\nu}(\text{normal})$ are neutrino luminosity with and without superfluid particles, respectively, and $R(T/T_{cr})$ is the reduction factor, i.e., the luminosity is suppressed by this factor in the presence of superfluidity. Roughly it reduces as $\exp(-a_{\nu}T_{cr}/T)$ (for $T \ll T_{cr}$, where $a_{\nu}$ is a constant), although the precise dependence is somewhat more complicated\textsuperscript{10}. The net effect is that in the presence of superfluidity a star cools more slowly due
• **Superfluid Suppression:**

• Fast cooling can be **suppressed** in the presence of superfluid particles: When particles are in a superfluid state, neutrino emissivity, specific heat, involving these particles, can be suppressed when \( T << T_{\text{crit}} \).

• where \( T_{\text{crit}} \) is superfluid critical temperature, which depends on superfluid energy gap, and \( T \) is the internal temperature of the star.

• \( T_{\text{crit}} \) depends on density.
Fig. 10: Superfluid Critical Temperature – Energy Gap

Fig. 2.— Various superfluid models, shown as the superfluid critical temperature $T_c$ versus matter density $\rho$ (in units of nuclear density) relation. For hyperon-mixed neutron matter, we show three representative models, ND-Soft (solid curves), Ehime (dashed curves) and FG (Fumabashi-Gifu type A) (dotted curves) for $\Sigma^-$ and $\Lambda$ hyperons as marked (in the higher density range of $\rho \geq 4\rho_0$, where $\rho_0$ is nuclear density). TNI6u EOS parameters are used. (The results from the other EOSs, TNI2u and TNI3u, are very similar as shown in Ta06.) The OPEG-A NN (nucleon-nucleon) interactions are adopted for neutron $^3P_2$ and proton $^1S_0$ superfluid models, marked $n$ and $p$ (solid curves), while the dash-dot curve shows neutron $^3P_2$ and $^1S_0$ (dotted line) with the OPEG-7 NN interaction.
• **Frictional heating due to vortex creep, in inner crust** (Anderson, Alpar, Pine; Umeda, Tsuruta, Nomoto 1995, etc.):

• In the inner crust, the friction between superfluid neutrons and crustal heavy nuclei cause heating

• The heavy ion crust spins down as the pulsar spins down, but superfluid neutrons do not. That causes friction. Superfluid neutron vortex is pinned to the crustal material, but when the difference in spinning speed exceeds some critical value, the vortex is unpinned and flows outward, causing friction and heating. The heating depends on strength of pinning – from this theory, can estimate maximum vortex creep heating allowed from theory.

• **Effect of Envelope Composition:** If the crust includes light elements, e.g., H, surface T increases due to increased conductivity.
Fig. 10: Current Thermal Evolution Model and Observed Temperatures
• Another method for Temperature measurement

• SXT in LMXB
• BeppoSAX, RXTE, XMM-Newton – X-ray burst observations

• Idea:
• Soft X-ray transients (SXT) in low-mass X-ray binaries (LMXB): in quiescence states provide strong constraints on thermal evolution theories (cooling and heating) of neutron stars (e.g., (*4), (*6)(*8)(*9)(*10))

• (*10) ST, et al. 2015, in preparation
Neutron Star Mini Nova:

- Accretion until critical density.
- Energy is produced by pycnonuclear reactions.
- Energy is spread over the neutron star via thermal conduction.
- Deep crustal heating.
- Photon emissions from the surface, neutrinos from the interior.
- Usually followed by quiescent period.
$L_{dh}(the\ deep\ nuclear\ heating\ power) = fn\ of\ Q,\ dM/dt.$

dM/dt = accretion\ rate\ averaged\ over\ the\ quiescent\ period\ (months\ to\ years)

$Q = the\ total\ amount\ of\ heat\ released\ per\ one\ accreted\ nucleon = \sim 1.45\ Mev\ and\ 1.12\ Mev\ (*9)$

\[ L_{dh}^∞ = L_v^∞ (T_{in}) + L_γ^∞ (T_{eff}), \]

\[ L_{dh} \left( \langle \dot{M} \rangle \right) = \frac{Q_{tot} \langle \dot{M} \rangle}{m_u} \approx 6.03 \times 10^{33} \langle \dot{M} \rangle_{-10} \frac{Q_{tot}}{\text{MeV}} \text{ erg.s}^{-1} \]

Here $L_{dh}^∞, L_v^∞ and L_γ^∞$, are the deep heating power, neutrino luminosity and photon luminosity observed at infinity. $T_{in}$ and $T_{eff}$ are the internal and surface temperature(*4)

(*9) Haensel and Zdunik, A and A, 1990,227, 117; 2003, 404, l33,
Photon Luminosity vs mass accretion rate;
- Unver and ST 2015
Tentative Conclusion - current:

Probably need:

• Non-standard fast cooling with superfluid suppression for cooler stars
• Need heating for some of hot stars
• The light element, e.g. H envelope needed for some of hot stars
• Stars with core with pion condensates and hyperons consistent with the current observed data for cooler stars
• Need more investigation for quark cooling
• Direct URCA with nucleons and kaons unlikely
Future work:

Pulsar thermal evolution: with more realistic EOS by T. Takatsuka, etc. - ST, K. Nomoto, M. Kelly, etc., in progress

Magnetar thermal evolution:
– too high from standard cooling process
Possible heating scenarios
(I) Heating from interior
(II) Heating from outside
• Heating from Interior

• Heyl and Hernquest, etc. Standard cooling of magnetar – hotter than pulsars, but
  Conclusion - not hot enough

• Kaminker et al 2006: MNRAS 371, 477
  Crust heating can be effective –
  Conclusion - If heating is $H > \sim 3 \times 10^{20}$ erg cm$^{-3}$/sec, get hot enough to agree with observed temperatures – but no heat source specified – purely empirical

  Reviews magnetar heating both in crusts and core.
  Used isothermal toy model, observation data – wrong

ST, K. Nomoto, and M. Kelly: in progress
  Use exact thermal evolution code; correct observational data, detailed simulation
(II) Heating from Outside:

First suggested by Nakagawa et al. 2009 PASJ 61, 109 (Makishima group) from Suzaku observation data –
Heating by solar-like microflares above the surface


Microflare Model: Quiet time - many microflares – energy carried from surface to magnetosphere – magnetic energy released by magnetic reconnection just above the surface – heat the surface

Reference: Masada, Nagataki, Shibata PASJ 2010, 62, 1093 – about magnetar giant flares, with magnetic reconnection model. –

Takeshige, K. Shibata, and ST, in progress