Thermal X-ray Emission from Isolated Neutron Stars

Isolated NSs: solitary NSs or those in binaries without accretion

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Neutron Star Crust and Surface: Observations and Models
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**Short history**

- Chiu & Salpeter (1964) and Tsuruta (1964): thermal radiation from the surface of a hot NS may be a source of cosmic X-rays

- First detections with Einstein (1978-81) and EXOSAT (1983-86): middle-aged PSRs B0656+14 and B1055-52, central compact sources in the SNRs RCW 103, Puppis A, PKS 1209-52, a few AXPs

- Since 1991, X-ray studies with ROSAT, ASCA, EUVE, BeppoSax, Chandra and XMM-Newton

In total, thermal emission detected from about 50-60 NSs:

- from the whole surface (atmospheres?) of cooling NSs

- from polar caps heated by relativistic particles streaming down onto the surface from pulsar's magnetosphere
**Thermal vs. Nonthermal**

emission in pulsars of different ages

Nonthermal (magnetospheric) emission, $~\dot{E} \sim t^{-\beta}$, $\beta \sim 2–4$

NSs cool down from $T \approx 10^{11}$ K (at birth) to 0.2–2 MK in 0.1–1 Myr

- **Young active (<1 kyr):**
  - nonthermal radiation dominates;
  - *Crab, B1509-58, B0540-69*

- **Middle-aged (10–100 kyr):**
  - thermal component from the whole surface;
  - *Vela, B0656+14, B1055-15, 6-ms J0437-4715, B0950+08*  

- **Old (>1 Myr):**
  - thermal emission from hot polar caps;

![Graphs showing the relationship between log energy and log flux for different age groups of pulsars, illustrating the dominance of nonthermal radiation in younger pulsars and the transition to thermal emission in older pulsars.](image-url)
Main questions

- Why is studying thermal emission needed?
- What is the state of the NS surface? Gaseous or liquid, or solid?
- What is the chemical composition of the NS surface? Hydrogen or heavier elements (e.g., iron)?
- What is the proper model for the thermal radiation?
Why is studying thermal emission needed?

Comparing observed emission with theoretical models \( \Rightarrow \)
\[ \Rightarrow T_{\text{surf}}, B, R, M \]

\( T_{\text{surf}}(t) \Rightarrow \) thermal evolution

\( R, M \Rightarrow \) constraints on EOS and internal structure

Surface chemical composition \( \Rightarrow \)
formation of NSs and their interaction with environment

What is the state of the NS surface?

It depends on \( T_{\text{surf}}, B \) and chemical composition.
For hydrogen, the surface is in a condensed state if:

\[ T_{\text{surf}} < 1 \times 10^5 \text{ K} \quad @ \quad B = 1 \times 10^{13} \text{ G} \]
\[ T_{\text{surf}} < 5 \times 10^5 \text{ K} \quad @ \quad B = 1 \times 10^{14} \text{ G} \quad \text{(Lai & Salpeter 1997)} \]
\[ T_{\text{surf}} < 1 \times 10^6 \text{ K} \quad @ \quad B = 5 \times 10^{14} \text{ G} \]
What is the chemical composition of the NS surface? Heavy elements or hydrogen?

A small amount of H,
surface density \( \sim 10^{-3} - 10^{-1} \text{ g/cm}^2 \)
total amount \( \sim 10^{10} - 10^{12} \text{ g} \),
due to accretion from ISM or fallback of material ejected during the SNR explosion.

Otherwise, heavier elements may be present.

What is the proper model for the thermal radiation?

Whatever is the physical state of the surface, its radiation should not be that of a black body.
Main aspects of the NS atmosphere modeling

What’s special about NS atmospheres?
Why not to use standard stellar atmosphere models?
1. Enormous gravity at the surface ($M \approx 1.4 \, M_\odot$, $R \approx 10$ km)

\[ g \approx 10^{14} \text{ vs. } 10^4 \, \text{cm}^2/\text{s} \text{ for usual stars} \]

⇒ NS atmospheres are strongly compressed

\[ \rho \approx 10^{-2} - 10^1 \text{ vs. } 10^{-7} \, \text{g/cm}^3 \]

height \approx kT_{\text{sur}}/m_p g \approx 10^{-1} - 10^1 \text{ vs. } 10^8 \text{ cm}

⇒ stratification of chemical elements

⇒ non-ideality effects (pressure ionization, smoothed spectral features)
2. Huge magnetic fields, $B = 10^{10} - 10^{14} \, G$

⇒ $E_{ce} = 11.6 (B/10^{12} \, G) \, \text{keV} \gg kT_{sur} \sim 0.1 \, \text{keV}$, $E \sim 0.1 - 1 \, \text{keV}$

⇒ NS atmospheres are essentially anisotropic

⇒ opacities depend on direction and polarization of radiation

⇒ radiation is polarized and depends on $B$

⇒ $\gamma = E_{ce} / (Z^2 \, \text{Ry}) = 850 \, Z^{-2} (B/10^{12} \, G) \gg 1$

⇒ atomic structure is distorted by $B$

⇒ increase of binding (ionization) energies of bound states

$I/(Z^2 \, \text{Ry}) \approx \ln^2(\gamma/Z^2) \gg 1$, $I_H \approx 0.2 \, \text{keV}$ at $B = 10^{13} \, G$

⇒ altered ionization equilibrium and equation of state
NS atmosphere models with "low" magnetic fields, \( B < 10^8 - 10^9 \, G \) (millisecond pulsars, NS transients in quiescence)

**General scheme (Mihalas 1978):**

- **radiative transfer in isotropic 1-D medium for specific radiative intensity** \( I_v(z, \mu) \)

\[
\mu \frac{d}{dy} I_v = k_v \left[ I_v - S_v \right], \quad \mu = \cos \theta = \vec{n} \cdot \vec{r}, \quad dy = -\rho \, dz
\]

\[
k_v = \sigma_v + \alpha_v \quad \text{— total radiative opacity, scattering+absorption}
\]

\[
S_v = \left[ \sigma_v J_v + \alpha_v B_v \right] k_v^{-1} \quad \text{— source function}
\]

\[
J_v = \frac{1}{2} \int_{-1}^{1} I_v \, d\mu \quad \text{— mean intensity}
\]

Comptonization is not important at \( T < 5 \times 10^6 \, \text{K} \)
Most common (diffusion) approach:

\[
\frac{d}{dy} k_v^{-1} \frac{d}{dy} f_v J_v = \alpha_v \left[ J_v - B_v \right]
\]

\[
k_v^{-1} \frac{d}{dy} f_v J_v = h_v J_v \bigg|_{y=0}
\quad \text{— no incident emission}
\]

\[
J_v = B_v \bigg|_{y \to \infty}
\quad \text{— equilibrium solution}
\]

the Eddington factors (accounting for anisotropy of radiation):

\[
f_v = \left[ 2 J_v \right]^{-1} \int_0^1 \mu^2 I_v \, d\mu \quad \left( \approx \frac{1}{3}, \quad y \to \infty \right)
\]

\[
h_v = \left[ 2 J_v \right]^{-1} \int_0^1 \mu \left[ I_v(\mu) + I_v(-\mu) \right] \, d\mu \quad \left( \approx \frac{1}{2} \right)
\]

\[
F_v = \frac{4\pi}{k_v} \frac{d}{dy} f_v J_v 
\quad \text{— spectral (monochromatic) flux}
\]
- radiative equilibrium (electron conductivity is not important)
  \[ \int_0^\infty d\nu \int_{-1}^1 \mu I_\nu \, d\mu = \sigma_{SB} T_{\text{eff}}^4 \rightarrow \int_0^\infty \alpha_\nu [J_\nu - B_\nu] \, d\nu = 0 \]

- hydrostatic equilibrium (radiative force is not important)
  \[ P = k_B N T = g y \]

- ionization equilibrium
  based on the occupation-probability formalism for non-ideal plasmas
  (e.g., Hummer & Mihalas 1988)
radiative opacities:
absorption due to free-free, bound-free and bound-bound transitions
the Thomson scattering on electrons

\[ k_\nu \sim E^{-3} \]
Model input: $T_{\text{eff}}, M, R$ (or $g$), chemical composition

Model output:

$F_v = 4\pi h_v J_v$ — spectral (monochromatic) flux at $y = 0$

$I_v = \mu^{-1} \int S_v k_v \exp\left[-\mu^{-1} \int k_v dx\right] dy$ — specific intensity

atmospheric structure:

$T(y), \rho(y)$
Spectra of nonmagnetic NS atmospheres

H \quad \log T_{\text{eff}} = 4.7, 5.3, 5.9, 6.5
He \quad g = 2.4 \times 10^{14} \text{ cm}^2 \text{ s}^{-1}
Fe
BB

Solar mixture
H - 70\%, He - 28\%, metals - 2\%

\log T_{\text{eff}} = 5.5, 6.0
Spectra of nonmagnetic NS atmospheres with various abundances of heavy elements

\[ T_{\text{eff}} = 10^8 \text{ K} \]

\[ B = 0 \]

Flux (erg s\(^{-1}\) cm\(^{-2}\) keV\(^{-1}\))

Energy (keV)

\[ Z = 2.0\% \]
\[ Z = 0.2\% \]
\[ Z = 0.05\% \]
\[ Z = 0.0\% \]
Angular dependences of specific intensities — radiation is anisotropic even in nonmagnetic case

limb-darkening effect
NS atmosphere models with strong magnetic fields, \( B = 10^{10} - 10^{14} \, G \)
(all ordinary pulsars, magnetars, radio-quiet INSs [?])

radiative transfer for two polarization modes, extra- and ordinary ones, with orthogonal polarizations
(Gnedin & Pavlov 1974)

\[
\mu \frac{d}{dy} I^j_v (\mathbf{n}) = k^j_v (\mathbf{n}) I^j_v (\mathbf{n}) - \\
- \left[ \sum_{i=1}^{2} \int d\mathbf{n}' I^i_v (\mathbf{n}') \sigma^{ij}_v (\mathbf{n}, \mathbf{n}') + \alpha^j_v (\mathbf{n}) \frac{B_v}{2} \right]
\]

\[
k^j_v (\mathbf{n}) = \alpha^j_v + \sigma^j_v , \quad \sigma^j_v = \sum_{i=1}^{2} \int d\mathbf{n}' \sigma^{ij}_v (\mathbf{n}, \mathbf{n}')
\]

— total radiative opacity, scattering+absorption

radiative and hydrostatic equilibrium
Diffusion approximation:

\[
\frac{d}{dy} D_v^j \frac{d}{dy} J_v^j - \sigma_v \left[ J_v^j - J_v^{3-j} \right] = \alpha_v^j \left[ J_v^j - \frac{B_v}{2} \right]
\]

\[
\alpha_v^j = \frac{1}{4\pi} \int d\mathbf{n} \alpha_v^j (\mathbf{n})
\]

\[
\sigma_v = \frac{1}{4\pi} \iint d\mathbf{n} d\mathbf{n'} \sigma_v^{12} (\mathbf{n}, \mathbf{n'})
\]

\[
D_v^j = D_v^j \cos^2 \Theta_B + D_v^j \sin^2 \Theta_B, \quad D_v^i = \int_0^1 \frac{\mu^2}{k_v^i} d\mu, \quad D_v^\perp = \frac{1}{2} \int_0^1 \frac{(1-\mu^2)}{k_v^i} d\mu
\]

\[
\cos \Theta_B = \mathbf{B} \cdot \mathbf{r}
\]

Model output: specific intensity and spectral flux at \( y = 0 \)

\[
I_v^j = \mu^{-1} \int_0^\infty \left[ \alpha_v^j \frac{B_v}{2} + \sum_{i=1}^{2} \sigma_v^{ij} J_v^i \right] \exp\left[ -\mu^{-1} \int_0^y k_v^i dx \right] dy
\]

\[
F_v^j = \int_0^1 \mu I_v^j d\mu
\]
NS atmosphere models with strong magnetic fields, $B = 10^{11} - 10^{14}$ G

Spectral flux (erg s$^{-1}$ cm$^{-2}$ keV$^{-1}$)

Energy (keV)

$B = 4.7 \times 10^{12}$ G
$B = 2.4 \times 10^{12}$ G
$B = 1.2 \times 10^{12}$ G

$g = 2.4 \times 10^{14}$ cm$^2$ s$^{-1}$
Log $T_{\text{eff}} = 5.6; 5.8; 6.0; 8.2$
Angular dependence of radiation from a magnetized NS atmosphere:

“pencil”-like structure along $\vec{B}$
“fan”-like structure at larger angles
proton cyclotron line
$B = 1 \times 10^{14} \, G$

electron cyclotron line
$B = 3 \times 10^{11} \, G$

atomic transitions
$T_{\text{eff}} < 5 \times 10^5 \, K$

$B = 2 \times 10^{12} \, G$

$E_{\text{ee}} = 3.5 \, \text{keV}$

$T_{\text{ee}} = 3.5 \times 10^6 \, K$

$B = 3 \times 10^{11} \, G$

$E_{\text{ee}} = 0.63 \, \text{keV}$

Hydrogen
$T_{\text{ee}} = 2.5 \times 10^6 \, K$

$B = 1 \times 10^{14} \, G$
Iron magnetized NS atmosphere models (Rajagopal et al. 1997)
More on hydrogen NS models for $B > 10^{14} - 10^{15} \, G$, fully ionized case:
studying vacuum-polarization effects (Gnedin et al. 1977):
conversion of normal modes of radiation —
in particular, it affects cyclotron lines (makes them very narrow)

More on partially ionized hydrogen atmosphere models:
Ho et al. 2003, Ho & Lai 2004 →
spectral features due to bound-free and bound-bound transitions

First magnetized NS atmosphere models for C, O, Ne chemical compositions (Mori et al. 2006)
Thermal emission as seen by a distant observer

General case: 

\[ F(E) = g_r \frac{1}{d^2} \int_S \mu I\left(g_r^{-1}E \right) dS \left[ \times \exp(-n_H \sigma) \right] \]

\[ g_r = \left[ 1 - \frac{2GM}{c^2 R} \right]^{1/2} \quad \text{— redshift parameter} \]

\[ E \quad \text{— observed (redshifted) energy} \]

\[ S \quad \text{— visible emitting area} \]

\[ d \quad \text{— distance to the object} \]

- nonuniform surface temperature and magnetic field
- gravitational bending of photon trajectories
- Doppler shifts of photon energies (for fast rotators)

Small heated spots (polar caps):

\[ F(E) = g_r \frac{S^a}{d^2} I\left(g_r^{-1}E, \mu^* \right) \]
Gravitational bending of photon trajectories

\[ g_r = \left[1 - \frac{2GM}{c^2 R}\right]^{1/2} \]

the whole surface is visible if \( g_r < 0.66 \)
Effect of the Doppler shift

Spectra from the whole surface of a nonmagnetized NS (iron atmosphere)
Light curves of radiation from a magnetized NS

- $M=1.4\ M_\odot$
- $R=10.7\ km$
- $T_p=1.8\ 10^6\ K$
- $B_p=10^{18}\ G$

**Axes:**
- Y-axis: Photons cm$^{-2}$ s$^{-1}$
- X-axis: Phase

**Graph:**
- Dipolar B, $T=T(\theta)$
- Dipolar B, $T=T_p$
- Orthogonal
- Rotator
- Dipolar B, $T=T(\theta)$, blackbody
- $N_H=0$, $D=100$ pc
- Uniform B=$B_p$, $T=T(\theta)$
Practical aspect: **NS atmosphere vs. blackbody model**

\[ \frac{T_{bb}}{T_{atm}} \approx 2-3 \]

\[ \frac{S_{atm}}{S_{bb}} \approx 50-200 \]
Successful applications of hydrogen atmosphere models:

- young pulsars, Vela, J0538+2817, B1706-44 (10—30 kyr), whose thermal emission originates from the whole NS surface of \( T > 1 \) MK

- millisecond and old pulsars with thermal X-ray component emitted from heated polar caps, J0437-4715, J2124-3358, J0030+0451, J1024-0719, B0950+08, J2043+2740

- compact central sources in the SNR Puppis A, RX J0822-4300, and in the SNR CTA 1, RX J0007+7302 — thermal emission from the whole NS surface

- transientsly accreting NSs in X-ray binaries, Aql X-1, Cen X-4, KS 1713-260, 4U 2129+47, MXB 1659-29 — quiescent radiation is interpreted as emitted from the whole NS surface due to heat released in the compressed material

- hydrogen atmosphere models can be useful for distinguishing between transientsly accreting NSs and black holes, in quiescence
NS atmospheres do not work:

middle-aged pulsars (100 — 300 kyr), Geminga, PSRs 0656+14, 1055-52...

old radio-quiet isolated NSs, RX J1856-3754, J0720-3125, J1308+2127...

These have lower surface temperatures, (0.5 — 0.7) MK, and high magnetic fields → atmospheres may not exist
Problems, future work

- bound-bound transitions in superstrong field $B > 10^{14} \, G$, when the lines get into observable X-ray range
- molecules and molecular chains in strong magnetic fields
- reliable models for partially ionized atmospheres for various chemical compositions
- radiative transfer approach based on two polarization modes is inaccurate for partially ionized plasma
- solving the radiative transfer equations for the four Stokes parameters using the polarizability tensor constructed with aid of the Kramers-Kronig relation
- “thin” atmosphere models — optically thick only at lower energies
From atmospheres to condensed surfaces

- solids and liquids in strong magnetic fields
- phase transition from atmospheres to condensed surface
- reliable models for emissivity of condensed surface