A Limit on Axion from the Cooling Neutron Star in Cassiopeia A

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Based on K. Hamaguchi, N. Nagata, K.Y., J. Zheng [1806.07151]
Short summary

Within the Standard Model

Cooling theory can fit the observed surface temperature of Cas A neutron star (NS)

SM + Axion

If the axion couplings to nucleons are too large, cooling is enhanced and cannot fit Cas A NS

\[ f_a > O(10^8) \text{ GeV} \]

comparable to the SN1987A limit
Outline

• Observation of neutron star in Cassiopeia A

• Cooling theory of a neutron star

• Axion emission from neutron star
Observation of neutron star in Cassiopeia A
Neutron star in the Cassiopeia A

Cassiopeia A

• Supernova remnant in the Cassiopeia constellation
• Distance: $d = 3.4^{+0.3}_{-0.1}$ kpc [Reed et al., Astrophys. J. 440, 706 (1995).]
• Birth date from remnant expansion: $1681 \pm 19$


  Age: $t \approx 340$ yr

Neutron star in Cas A (Cas A NS)

• Point source in the center of Cas A
• Thermal X-ray spectrum detected by the Chandra [Tananbaum (1999)]
• Carbon atmosphere fit: $M = (1.4 \pm 0.3) M_\odot$
Cooling of Cas A NS

Surface temperature detected for 14 years

\[ T_s^\infty = T_s \sqrt{1 - 2GM/R} \]

- First direct observation of NS cooling
- Temperature decrease:

\[ \left( \frac{\Delta T_s^\infty}{T_s^\infty} \right)_{CasA} = 3 - 4\% / 10 \text{ year} \]

Can we explain this decrease?

Yes! (blue line: theory)

- BSk21:1.441 \( M_{\odot} \)
- Fe envelope
- ns-SFB
- ps-CCDK
- nt-TToa

\[ \chi^2/\text{dof} = 4.4/8 \]

[Ho et al. (2015)]
Cooling theory of neutron star
Cooling theory of NS without Cooper pairing

Thermal balance equation

\[ C \frac{dT}{dt} = -L_\nu - L_\gamma \]

- Internal temperature
- Neutrino luminosity
- Heat capacity \((n, p, e, \mu)\)
- \(C \propto T\)
- Photon luminosity: \(L_\gamma = 4\pi R^2 \sigma_B T_s^2\)
Cooling theory of NS without Cooper pairing

Thermal balance equation

Internal temperature

Neutrino luminosity

Heat capacity ($n, p, e, \mu$)

$C \propto T$

Photon luminosity: $L_\gamma = 4\pi R^2 \sigma_B T_s^2$

negligible at Cas A age \(\sim 340\) yr
Cooling theory of NS without Cooper pairing

Thermal balance equation

\[ C \frac{dT}{dt} = -L_\nu - L_\gamma \]

Internal temperature

Neutrino luminosity

Heat capacity \((n, p, e, \mu)\)

\[ C \propto T \]

Photon luminosity:

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

negligible at Cas A age \(~ 340 \text{ yr}\)

Neutrino emission

- **Direct Urca process**
  \[ n \rightarrow p + \ell + \bar{\nu}_\ell \quad p + \ell \rightarrow n + \nu_\ell \]

- **Modified Urca process**
  \[ n + N \rightarrow p + N + \ell + \bar{\nu}_\ell \quad p + N + \ell \rightarrow n + N + \nu_\ell \]
Cooling theory of NS without Cooper pairing

Thermal balance equation

\[ C \frac{dT}{dt} = - L_\nu - L_\gamma \]

Internal temperature

Neutrino luminosity

Heat capacity \((n, p, e, \mu)\)

\[ C \propto T \]

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

negligible at Cas A age \(\sim 340\) yr

Neutrino emission

- **Direct Urca process** \( L_{\nu}^{\text{DU}} \propto T^6 \)
  
  \[ n \rightarrow p + \ell + \bar{\nu}_\ell \quad p + \ell \rightarrow n + \nu_\ell \]

- **Modified Urca process** \( L_{\nu}^{\text{MU}} \propto T^8 \)
  
  \[ n + N \rightarrow p + N + \ell + \bar{\nu}_\ell \quad p + N + \ell \rightarrow n + N + \nu_\ell \]
Cooling theory of NS without Cooper pairing

Thermal balance equation

\[ C \frac{dT}{dt} = -L_\nu - L_\gamma \]

- Internal temperature
- Neutrino luminosity
- Heat capacity \((n, p, e, \mu)\)
- Photon luminosity: 
  \[ L_\gamma = 4\pi R^2 \sigma_B T_s^2 \]
  negligible at Cas A age \(\sim 340\) yr

Neutrino emission

- Direct Urca process 
  \[ L_{DU}^\nu \propto T^6 \]
  forbidden for \(M \lesssim 2M_\odot\)
  \[ n \rightarrow p + e^+ + \nu_e \quad p + e^+ \rightarrow n + \nu_e \]

- Modified Urca process 
  \[ L_{MU}^\nu \propto T^8 \]
  \[ n + N \rightarrow p + N + e^+ + \nu_e \quad p + N + e^+ \rightarrow n + N + \nu_e \]
Cooling theory of NS with Cooper pairing

Thermal balance equation

\( T < T_c \), neutrons and protons form Cooper pairs

\[
\epsilon_N(k) = \mu_{F,N} + \text{sign}(k - k_{F,N}) \sqrt{\Delta_N^2 + (k - k_{F,N})^2}
\]

Energy gap

\( \text{O}(0.1 - 1) \text{ MeV} \sim \text{O}(10^{9-10}) \text{ K} \)

In NS core
- Proton singlet pairing \((^1S_0)\)
- Neutron triplet pairing \((^3P_2)\)

Neutrino emission
- Direct Urca process \( L_{\nu}^{\text{DU}} \propto T^6 \)
  \( n \rightarrow p + \ell + \bar{\nu}_\ell \quad p + \ell \rightarrow n + \nu_\ell \)
- Modified Urca process \( L_{\nu}^{\text{MU}} \propto T^8 \times \text{(exponential supression)} \)
  \( n + N \rightarrow p + N + \ell + \bar{\nu}_\ell \quad p + N + \ell \rightarrow n + N + \nu_\ell \)
- Pair-breaking and formation (PBF)
  \( \bar{N} + \bar{N} \rightarrow [\bar{N}\bar{N}] + \nu + \bar{\nu} \)
  dominant for \( T < T_c \)
Neutron triplet pairing explains the rapid cooling of Cas A NS!

- Modified Urca suppressed by proton pairing
- Onset of neutron $^3P_2$ pairing
- Rapid cooling by neutron PBF
- First observation of neutron superfluidity in NS

Proton $^1S_0$ pairing
- Large $T_c$ is necessary to avoid overcool by modified Urca before $t \sim 330$ yr

$$T_c^{(p)} \gtrsim 10^9 \text{ K}$$
Axion emission from neutron star
Axion couplings to nucleons

Next, we consider **SM + Axion**

- **Axion:** a Nambu-Goldstone boson associated with Peccei-Quinn symmetry [Pecci and Quinn (1977); Weinberg (1978); Wilczek (1978)]

\[
\mathcal{L} = \frac{1}{2} \left( \partial_\mu a \right)^2 + \frac{1}{f_a} \frac{\alpha_S}{8\pi} G_{\mu\nu} \tilde{G}^{\mu\nu} + \sum_q \frac{C_q}{2f_a} \bar{q} \gamma^\mu \gamma_5 q \partial_\mu a + \ldots
\]

- **Axion couplings to nucleons**

\[
\mathcal{L} = \sum_{N=n,p} \frac{C_N}{2f_a} \bar{N} \gamma^\mu \gamma_5 N \partial_\mu a + \ldots
\]

- **Model dependence**

  **KSVZ model:** \( C_p = -0.47(3), \ C_n = -0.02(3) \) \( (C_q = 0) \) \[\text{Kim (1979); Shifman, Vainshtein, Zakharov ((1980))}\]

  **DFSZ model:** \( C_p = -0.182(25) - 0.435 \sin \beta^2 \)

  \[ C_n = -0.160(25) + 0.414 \sin \beta^2 \] \( (C_{u,c,t} = \frac{1}{3} \cos \beta, C_{d,s,b} = \frac{1}{3} \sin \beta^2) \) \[\text{Zhitnitsky (1980); Dine, Fischler, Srednicki (1981)}\]
Axion emission from neutron star

Extra cooling by axion

\[ C \frac{dT}{dt} = -L_\nu - L_a \]

- Axion Bremsstrahlung

- Axion PBF

\[ \tilde{N} + \tilde{N} \rightarrow [\tilde{N}\tilde{N}] + a \]

Even if \( C_n \sim 0 \), axion emission is sizable due to the proton contribution!
Limit on axion decay constant

For fixed $f_a$, we vary the neutron gap profile to fit the Cas A NS temperature. If the fit fails for any gap parameter, we exclude that axion model.

$$f_a \gtrsim 5 \left(7\right) \times 10^8 \text{GeV}$$

$T^8_s$ 

For $T^8_s$, we vary the neutron gap profile to fit the Cas A NS temperature. If the fit fails for any gap parameter, we exclude that axion model.

$$f_a \gtrsim 4 \times 10^8 \text{GeV}$$

the fit fails for any gap profile

NS is overcooled before neutron Cooper pairing

comparable to the limit from SN1987A
Uncertainty from envelope

**Envelope:** composed of light element (H, He, ...) and heavy element (Fe)

Characterized by

\[ \eta = g_{14}^2 \Delta M/M \]

mass of light elements

We do not know \( \eta \)

We evaluate the uncertainty from envelope

\[ f_a > O(10^8) \text{ GeV} \]
Summary

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Neutron triplet pairing is important

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\[ f_a > O(10^8) \text{ GeV} \]

comparable to the SN1987A limit

O(1) uncertainty from envelope profile

Backup
Why Cas A NS is special?

In Cas A NS, temperature decline rate is available
More powerful to constrain cooling theory

Cas A NS: 14 years data \{ (t_0, T_{s,0}^\infty), (t_1, T_{s,1}^\infty), \ldots \}

Other NS:
• About 30 observations of surface temperature
• Single measurement of \((t, T_s^\infty)\) for each NS

[Page et al. (2004)]

[Yakovlev et al. (2008)]
Summary of neutrino emission

- Direct Urca process is powerful, but forbidden in Cas A NS
- Weaker Modified Urca dominates before Cooper pairing
- After pairing, the PBF process dominates the cooling

![Diagram showing the relationship between neutrino luminosity (L) and core temperature (Tcore) with lines for Modified Urca, PBF, and Photon processes.](image)
Proton singlet gap model

Theoretical calculations are relatively certain

We use CCDK model because

• Large proton gap is more favorable for Cas A
• Axion emission from proton is suppressed

→ derived bound on \( f_a \) is conservative
Neutron triplet gap model

Theoretical calculations are highly uncertain

We model the gap by the Gaussian

3 parameters

- Height $T_c^{(n)}$
- Width
- Center
How to constrain the axion model?

If SM + axion cannot fit the Cas NS, the model is excluded

constraint on $f_a$

$$\mathcal{L} = \sum_{N=n,p} \frac{C_N}{2f_a} \bar{N} \gamma^\mu \gamma^5 N \partial_\mu a + \cdots$$

Cooling model parameters

- Neutron $^3P_2$ gap model → vary to fit Cas A NS (3 parameter Gaussian model)

- Proton $^1S_0$ gap model → does not matter as long as large enough (we use CCDK model) [Chen et al. (1993)]

- Neutron $^1S_0$ gap model → SFB model

- Equation of state → APR

- NS mass → $M = 1.4M_\odot$

not so sensitive to these choices