Axion Limit from the Cooling Neutron Star in Cassiopeia A

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Base on
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Axion

- Axion is the pseudo-Goldstone boson of PQ symmetry
- Solves strong CP problem

Astrophysical constraints:

What about neutron star

*PDG 2018*
Summary

The rapid cooling of CAS A NS was observed

- The cooling can be explained in the standard cooling model
- Axion enhances the cooling and get constrained
Outline

- Neutron star cooling, theory
- CAS A NS cooling, obs. vs theory
- Axion emission from CAS A NS, constraint
- Summary
Neutron Star Cooling, theory

Neutron star interior is almost isothermal after relaxation time scale $\sim 100 \text{ yr}$

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

Photon is emitted only from the surface:

$$L_\gamma = 4\pi R^2 \sigma_{SB} T_e^4$$

$L_\gamma \ll L_\nu$ for $t \lesssim 10^6 \text{ yr}$

$t \approx 300 \text{ yr}$ for CAS A

Internal $T$ is determined from $T_e$ by envelope model

For a review, c.f. 1302.6626
Envelope model

\[ L_\gamma = 4\pi R^2 \sigma_{SB} T_e^4 \]

- \( T_e \) Effective temperature
- \( T_b \) Internal temperature below the envelope
- \( \eta \sim \Delta M/M_{NS} \)
- \( \Delta M \) Mass of light element (H/He/C) in the envelope
- \( \eta \rightarrow 0: \) Fe envelope

\[ T_e \approx T_b^\alpha \quad \alpha \sim 0.5 \]

**Major uncertainty:**

The composition of envelope, and thus \( \eta \) is unknown ..
Neutrino emission

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

- Direct URCA process (fast)

\[ n \rightarrow p + e^- + \bar{\nu} \]

\[ p + e^- \rightarrow n + \nu \]

Highly suppressed for \( M \lesssim 2M_\odot \)

Emission take place near Fermi surfaces:

\[ p^{p,n,e}_F \approx p^{p,n,e}_F \]

Charge neutrality:

\[ E_F^p = E_F^e \]

Chemical equilibrium:

\[ E_F^n = E_F^p + E_F^e \]

Contradicts energy–momentum conservation

\( M \gtrsim 2M_\odot \): muon is produced in higher density medium
Neutrino emission

• Modified URCA process (slow)

\[ N + n \rightarrow N' + p + e^- + \bar{\nu} \]
\[ N + p + e^- \rightarrow N' + n + \nu \]

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

\[ N \ n \ N' \ p \ e \ \nu \ \delta \ E \]
\[ T \ T \ T \ T \ T \ T^3 \ T^{-1} \ T \]
\[ L \sim T^8 \]

Power law cooling:

\[ L_\nu = hT^\alpha, \ C = cT \]
\[ \frac{1}{T^{\alpha-2}} = \frac{1}{T_i^{\alpha-2}} + \frac{(\alpha - 2)h\Delta t}{c} \]

• Larger \( \alpha \): slower cooling
• For \( T << T_i \), \( T_i \) doesn’t matter
• \( T \sim \Delta t^{-\frac{1}{\alpha-2}}, \ T_e \sim \Delta t^{-\frac{1}{2\alpha-4}} \)
Neutrino emission

- Nucleon form cooper-pairs at low $T$

$$T_c \sim \Delta(T = 0) \sim \mathcal{O}(1 \text{ MeV})$$

- Suppress emission from nucleon $\sim \exp(-N\Delta/T)$
- Reduces specific heat for $T < T_c$
Neutron $^1S_0$

Proton $^1S_0$

$^1S_0$ is repulsive at high density:
- Neutron $^1S_0$ in crust
- Proton $^1S_0$ in core

HUGE theoretical uncertainty
Neutrino emission

- The pair-breaking-formation process (PBF)

\[ N + N' \rightarrow [NN'] + \nu + \bar{\nu} \]

equivalently,

\[ \tilde{N} + \tilde{N}' \rightarrow \nu + \bar{\nu} \]

\[ L \sim T^7 R \sim T^7 \exp(-2E/T) \]

\[ \tilde{E}_p = \sqrt{\epsilon_p^2 + \Delta_p^2} \]

\[ \epsilon_p = v_F (p - p_F) \]

This causes a momentary rapid cooling
relaxation

phase transition

photon cooling

neutrino cooling

\[ T_{\text{max}}^{10^9\text{K}} = 1.6 \ 0.4 \ 0.2 \ 0 \]

Age [yrs]

\[ T_\infty \ \text{[10^6K]} \]
The CAS A NS (OBS)

- John Flamsteed: 3 CAS? (1680)

- Remnant expansion: SN exploded in 1681 ± 19
- NS x-ray found by Chandra in 1999
The Cooling of CAS A NS (OBS)

Heinke & Ho, *Nature* 2010:

Cooling by $2 \sim 4\% / 10$ yrs

$M = 1.4 \pm 0.3 \ M_\odot$

Can we explain it with standard cooling?
The Cooling of CAS A NS (TH)

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

D. URCA is irrelevant: 

\[ M = 1.4 \pm 0.3 \, M_\odot < 2M_\odot \]

Even if it is, \( T \) would be too low

M. URCA is too slow:

\[ L \sim T^8, \quad C \sim T \]

\[ T_e \sim T^{\frac{1}{2}} \]

\[ \left( \frac{\Delta T_e}{T_e} \right)_{10 \text{ yrs}} \sim -\frac{1}{12} \frac{\Delta t}{t} \sim 0.3\% \]

\[ \ll (2 \sim 4)\% \]

A rapid process is needed to explain the fast cooling of the CAS A NS
The Cooling of CAS A NS (TH)

Page, Prakash, Lattimer, Steiner, PRL 2011
Shternin, Yakovlev, Heinke, Ho, Patnaude, 2012 MNRAS:

CAS A NS rapid cooling can be explained by PBF pairing model tuned to fit the data (Tc in particular)

● Large model uncertainty in triplet pairing

Envelope with a thin light element layer:

\[ \eta = 5 \times 10^{-13} \]

Otherwise, T is too low to fit the slope.

Viewed as direct evidence of phase transition in NS
Axion emission in NS

Axion emitted mainly by nucleon

Axion–nucleon coupling:

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

- **KSVZ**: \( C_p = -0.47(3), \ C_n = -0.02(3) \)  
  (This talk)

- **DFSZ**: \( C_p = -0.182(25) - 0.435 \sin^2 \beta, \)  
  \( C_n = -0.160(25) + 0.414 \sin^2 \beta \)
Axion emission in NS

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

Dominant processes

**PBF**

\[ L \sim T^5 \]

\[ L \sim T^7 \]

**Bremsstrahlung**

\[ L \sim T^6 \]

\[ L \sim T^8 \]
Axion emission in CAS A NS

Some technical detail:

We used the public code NSCool for simulation and added extra cooling by axion emission. PBF

Bremsstrahlung

To be conservative on axion limit:

Proton $^1S_0$: CCDK (Highest $T_c$)

- Suppress axion emission
- Prevent over cooling by MURCA

Neutron $^3P_2$: Gaussian with free parameter

Choice of convenience:(doesn’t matter)

- APR EOS
  - Neutron $^1S_0$: SFB (only relevant to relaxation)
  - $M = 1.4 \pm M_\odot$
Axion emission in CAS A NS

Axion luminosity in KSVZ:

Proton PBF emission dominates $L_a$

Phase transition

$L_p^S \propto v_F$

$v_F \sim 0.2$

in the neutron star core

This process is ignored in earlier work of CAS A NS axion cooling.
Axion emission in CAS A NS

Cooling with axion vs data

KSVZ, $\eta = 5 \times 10^{-13}$

$T_8^8$ [K]

$2 \times 10^6$

$10^6$

$320$ $340$

Time [year]

$4 \times 10^8$ GeV

$6 \times 10^8$ GeV

$1 \times 10^9$ GeV

$\eta = f_a \times 10^8$ GeV

$f_a \gtrsim 5 \times 10^8$ GeV

KSVZ, assume thin carbon layer

SN1987A limit: $f_a \gtrsim 4 \times 10^8$ GeV

evelope with thin light element layer
Axion emission in CAS A NS

\( T_{\text{core}} \) from cooling model at \( t_{\text{obs}} = 2001 \) vs \( f_a \)

\( n^3 P_2 \) pairing turned off

\[ O(1) \times 10^8 \text{GeV} \text{ uncertainty} \]
More on envelope uncertainty

We can do better for KSVZ! \( C_n \sim 0 \), \( n^3 P_2 \) PBF emits \( \nu \) not \( a \)

\[
T_c = 2.2 \times 10^8 K, \quad \eta = 10^{-8}, \quad T_0 = 1681
\]

\[
\eta = 10^{-10}
\]

Large \( \eta \) \[\Rightarrow\] low \( T_b \) \[\Rightarrow\] low \( L_\nu \) \[\Rightarrow\] Cannot fit the slope by neutrino alone

**Neutron PBF**

**KSVZ:** Neutrino only \[\Rightarrow\] Low \( \eta \) \[\Rightarrow\] \( f_a \gtrsim 5 \times 10^8 \) GeV

**DFSZ:** Neutrino + axion \[\Rightarrow\] Any \( \eta \) \[\Rightarrow\] \( f_a \gtrsim 1 \times 10^8 \) GeV
The axion mean free path

Determined by the inverse proton PBF:

$$a \rightarrow \bar{p} + \bar{p}$$

$$\Gamma_{a\rightarrow\bar{p}\bar{p}} \sim \frac{m_p^* p_F v_F^2 T}{3\pi f_a^2} \left(\frac{C_p}{2}\right)^2$$

For simplicity, take $$l_a = 1/\Gamma_{a\rightarrow\bar{p}+\bar{p}} \gtrsim 10\text{km}$$

For $$p_F \sim 100\text{ MeV}, m_p^* \sim 1\text{ GeV}, T \sim \Delta_p \sim 1\text{ MeV},$$

$$f_a \gtrsim \left(\frac{C_p}{2}\right) \times 10^6\text{ GeV}$$

otherwise, the axion is reabsorbed back to the NS
Summary

- The rapid cooling of CAS A NS is observed and explained by the standard model;
- Axion emission enhances the cooling and get constrained
- We obtained a tight bound for KSVZ, \( f_a \gtrsim 5 \times 10^8 \text{ GeV} \)
  For DFSZ the bound is weakened, \( f_a \gtrsim 1 \times 10^8 \text{ GeV} \), due to the uncertainty of the NS envelope.
- For comparison, these are comparable to the SN1987A bound: \( f_a \gtrsim 4 \times 10^8 \text{ GeV} \)
- Mean free path of the axion requires \( f_a \gtrsim \left(\frac{C_p}{2}\right) \times 10^6 \text{ GeV} \)
  for the bound to be valid.
Uncertainty?

- Envelope: Major uncertainty. We estimated it.

- Data: Mostly on the cooling part by contamination of camera. We only rely on this for KSVZ. The average temperature give us a weaker bound. Future experiment?

- Relaxation time scale: The relaxation is already simulated by NSCOOL. There were proposals of longer relaxation after the discovery of the rapid cooling of CAS A NS. Need better understanding or analyze an older neutron star.
Thank You !
BACKUP SLIDES
Neutron $^3P$–$F_2$ gap: "a2" ($T_c^{\text{max}} = 5.5 \times 10^8 \text{K}$)