Hybrid cooling of the Cassiopeia A neutron star

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ABSTRACT
The observed rapid cooling of the neutron star Cassiopeia A is usually interpreted as being caused by transitions of neutrons and protons in the star’s core from the normal state to the superfluid and superconducting state. However, this so-called "minimal" cooling paradigm faces the problem of numerically simulating the observed anomalously fast drop in the neutron star surface temperature using theoretical neutrino energy losses from superfluid neutrons. As a solution to this problem, I propose a somewhat more complex cooling model, in which, in addition to superfluid neutrons, direct Urca processes from a very small central part of the neutron star core are also involved. Numerical simulations of the cooling trajectory in this scenario show excellent agreement with observations of the Cassiopeia A neutron star. The proposed cooling scenario unambiguously relates the used equation of state and the mass of the neutron star. For a neutron star constructed according to BSk25 equation of state, the most appropriate are the mass $M = 1.62M_{\odot}$ and the radius $R = 12.36$ km. If BSk24 equation of state is used, then the most suitable solution is $M = 1.60M_{\odot}$ and $R = 12.55$ km.

Key words: dense matter – stars: neutron – neutrinos – supernovae: individual: Cassiopeia A – X-rays: stars

1 INTRODUCTION
The neutron star (NS) in the supernova remnant Cassiopeia A (Cas A), discovered by the Chandra satellite in 1999 (Hughes et al. 2000), is of exceptional interest to astrophysicists. At a sufficiently low surface magnetic field of $10^{10} - 10^{11}$ G, the $X$-ray radiation of this hot isolated superdense object can be unambiguously associated with the temperature of its surface, neglecting the non thermal X-ray radiation of the magnetosphere. In this regard, the study of the thermal evolution of this young ($\approx 340$ yr old, Fesen et al. 2006) neutron star in X-rays is of great importance for a better understanding of the evolution of such superdense objects and makes it possible to study their composition and structure (see, e.g. Page et al. 2004, 2009; Yakovlev & Pethick 2004a).

About ten years ago, Ho & Heinke (2009) and Heinke & Ho (2010) analyzed a decade of Chandra observations of the Cas A supernova remnant and reported a sustained anomalous drop in the star surface temperature $T_s$, a phenomenon that had never been observed for any isolated neutron star. Despite significant corrections to the observational data over next 10 years, the decrease in the temperature of the neutron star is still anomalously fast. Current analysis (Posselt & Pavlov 2018; Wijngaarden et al. 2019; Ho et al. 2021) gives upper limits corresponding to a 3.3% or 2.4% decrease in temperature over 10 years depending on values of the absorbing hydrogen column density. Such a rapid drop in surface temperature contradicts the standard neutrino cooling scenario based on efficient modified Urca processes. If the NS in Cas A were to undergo standard cooling, then the drop in its surface temperature over 10 years would be 0.2% – 0.3% (Yakovlev et al. 2001; Page et al. 2006).

To explain these observations, various exotic energy loss mechanisms have been proposed using nonstandard assumptions about the physics and evolution of NSs, including softened pion modes (Blaschke et al. 2012a), quarks (Sedrakian 2013; Noda et al. 2013) and cooling after heating process in r-mode Yang et al. (2011) or turbulent magnetic field (Bonanno et al. 2014). Other scenarios have been proposed, suggesting the so-called "enhanced" cooling due to direct Urca processes (Negreiros et al. 2013; Taranto et al. 2016) or additional emission of axions. (Leinson 2014, 2021; Hamaguchi et al. 2018). Except in the case of additional energy losses because of the axion emission, the rapid cooling in these scenarios occurs from the birth of a NS, so the current temperature must be much lower than actually measured. The rapid decrease, but relatively high surface temperature (about $2 \times 10^6$ K) indicates that the cooling was slow at first, but then accelerated significantly, which requires a sharp change in the properties of neutrino emission from NS. (Page et al. 2011; Shternin et al. 2011).

With this in mind, it has been suggested that the observed rapid temperature drop can be naturally explained in terms of the minimum cooling paradigm (Page et al. 2004, 2009), where the rapid cooling of a neutron star is caused by the neutron superfluidity in the core. This scenario assumes that neutrons have recently become superfluid (in the $^3P_2$ state) in the NS core, causing a huge flux of neutrinos as a result of...
the Cooper pairs breaking and formation (PBF) in thermal equilibrium (Page et al. 2011; Shternin et al. 2011), and protons already in the superconducting singlet state $^3S_0$ with a higher critical temperature suppress modified Urca processes.

The PBF emission of neutrinos occurs mainly owing to spin fluctuations of neutrons, since in the considered long-wavelength limit, the emission of neutrinos in the vector channel is completely suppressed (Leinson & Perez 2006; Steiner & Reddy 2009). The correct form of the PBF neutrino emissivity of the $^3P_2$ superfluid neutrons, as derived in (Leinson 2010) (for recent review see Leinson 2018), reads:

$$Q^{\text{PBF}}_{n\nu} \simeq \frac{2}{15\pi^5} G_F^2 C^2_{F_{n\nu}} m_n^5 N_{\nu} T^6 F_4 \left( \frac{T}{T_{cn}} \right),$$

(1)

where $G_F = 1.166 \times 10^{-5}$ GeV$^{-2}$ is the Fermi coupling constant, $C_A = 1.26$ is the axial-vector coupling constant of neutrons, $p_{Fn} = m_{n}\pi^{-1}$ is the Fermi momentum of neutrons, $m_n \equiv p_{Fn}/V_{Fn}$ is the neutron effective mass, $N_{\nu} = 3$ is the number of neutrino flavors, and $T_{cn}$ is the critical temperature for neutron pairing; the function $F_4$ is given by

$$F_4 \left( \frac{T}{T_{cn}} \right) = \int_0^\infty \frac{dz}{\pi} \frac{z^4}{(\exp z + 1)^2},$$

(2)

with $n = p/p$ ($p$ is a quasiparticle momentum) and

$$z = \sqrt{x^2 + \Delta_n^2 / T^2}.$$  

(3)

The superfluid energy gap

$$\Delta_n (\theta, T) = \Delta (T) \sqrt{1 + 3 \cos^2 \theta},$$

(4)

is anisotropic. It depends on polar angle $\theta$ of the quasiparticle momentum and temperature $T$.

In standard physical units Eq. (1) takes the form

$$Q^{\text{PBF}}_{n\nu} = \frac{4G_F^2 p_{Fn} m_n^5}{15\pi^5 h m^6 c^6} (k_B T)^7 N_{\nu} C^2_F \left( \frac{T}{T_{cn}} \right),$$

(5)

$$= 1.170 \times 10^{31} \frac{m_n^5 p_{Fn} T^7}{m_n m_{oc}} \frac{N_{\nu} C^2_F}{2} \left( \frac{T}{T_{cn}} \right) \frac{\text{erg}}{\text{cm} \cdot \text{s}},$$

with $T_0 = T/10^9 K$ and $m_n$ being the bare neutron mass.

According to the minimal cooling scenario neutrino energy losses from neutron pairing in the NS core are responsible for the observed rapid temperature drop. However, numerical simulations (Shternin et al. 2011; Shternin & Yakovlev 2015; Potekhin & Chabrier 2018) have shown that PBF processes in the neutron spin-triplet condensate are not efficient enough to reproduce the observed rapid cooling of Cas A NS reported in (Ho & Heinke 2009; Heinke & Ho 2010), which makes it difficult to successfully explain the observational data (Shternin et al. 2011; Shternin & Yakovlev 2015; Potekhin & Chabrier 2018; Shternin et al. 2021).

To adapt the simulation result in the minimum cooling scenario with the observational data, the authors increased the PBF neutrino emissivity several times by multiplying the expression (5) by the scaling factor (Shternin et al. 2011; Elshamouty et al. 2013; Shternin et al. 2021). This approach is questionable because the energy losses, as indicated in Eq. (5), were calculated microscopically, taking into account many-particle effects with the same accuracy as other neutrino processes involved in the cooling scenario. In particular, this expression involves anomalous weak interactions (existing only in superfluid Fermi liquids), which significantly reduce the emission of PBF neutrinos. Note that a similar result was obtained in (Kolomeitsev & Voskresensky 2008) for the PBF neutrinos emitted through the axial channel in the case of neutron spin-singlet pairing. It was also demonstrated there (see also Leinson 2013) that the polarization effects in nucleon matter can only slightly reduce the emission of PBF neutrinos. Thus, the energy losses indicated in the Eq. (5) are quite accurate and cannot be arbitrarily enlarged by a scale factor.

A natural question arises: why the existing theoretical models of the Cas A NS cooling disagree with observational data? As will be shown below, this ten-year-old problem can be easily solved simply by going beyond the minimal cooling paradigm and choosing the NS mass so that the direct Urca processes are activated in a very small central part of the NS core. The observed anomalously close in the NS surface temperatur in this case is provided by joint losses of neutrinos from direct Urca reactions and the neutrino emission from PBF processes dominating in the current period. Since this scenario combines "minimal" and "enhanced" cooling, I call it "hybrid" cooling.

In Section 2, I briefly describe the NS model, including the EOS and superfluid and superconducting gaps. In Section 3 I present the simulation results. Finally, I summarize and discuss my findings in Section 4.

### 2 Neutron Star Model

The exact mass of Cas A NS is not directly observed. The measured energy spectra of the X-ray flux mainly depend on the brightness and gravitational redshift, which are functions of the NS mass $M$ and radius $R$. Fitting of the observational data with theoretical models showed (Elshamouty et al. 2013) that the most suitable mass is $M \simeq 1.62 M_\odot$, later a wider mass range was proposed, $M \sim (1.6 \div 1.65) M_\odot$, depending on the accepted equation of state (EOS) (Heinke & Ho 2010; Ho et al. 2015, 2021; Shternin et al. 2021). The Cas A NS model, considered below, uses the most modern EOSs based on the Brussels-Skyrme nucleon interaction functional, BSk24, BSk25 (Pearson et al. 2018), which have been precisely fitted to almost all available data on atomic mass and constrained to fit up to the densities prevailing in neutron-star cores. Note that the most suitable mass of the Cas A NS exceeds the fast direct Urca cooling threshold $M_{\text{dU}}$ for both the EOSs: $M_{\text{dU}} = 1.595 M_\odot$ and $M_{\text{dU}} = 1.612 M_\odot$ for BSk24 and BSk25, respectively. Thus, direct Urca processes are involved in the hybrid cooling of Cas A NS.

Superfluidity of neutrons and superconductivity of protons still play an important role in the hybrid scenario of NS cooling, partially suppressing the heat capacity and standard mechanisms of neutrino emission of nucleons. The most important role is assigned to the enhanced PBF emission of neutrinos owing to Cooper pairing of neutrons, when the temperature drops just below the critical value $T_{\text{cn}}$ in the NS core.

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1. The definition of the gap amplitude in Eq. (4) matches what is implemented in the public NSCool code by Page (2010) and differs from the gap definition used in refs. (Leinson 2010, 2018) by $1/\sqrt{2}$ times.
2. Notice, the neutrino emissivity, as indicated in Eq. (1), is 4 times less than that implemented in the NSCool code.
To simulate Cas A NS cooling, I use the widely used CCDK model (Elgaroy et al. 1996) for the $^1S_0$ proton gap, which can create NSs with a completely superconducting core of protons (Ho et al. 2015). As was found in (Page et al. 2011; Shternin et al. 2011), the critical temperature for the superfluid transition of neutrons as a function of density should have a broad peak with a maximum $T_{cs}(\rho) \approx (5-8) \times 10^8$ K. Therefore, the TToa (Takatsuka & Tamagaki 2004) model is used for the $^3P_2$ neutron gap in the NS core. For singlet pairing of neutrons the "SFB" model (Schwenk et al. 2003) is chosen. The choice of other models for the singlet pairing of neutrons slightly affects the result, since the $^1S_0$ pairing of neutrons occurs only in the inner NS crust.

By solving the standard Tolman–Oppenheimer–Volkoff relativistic equations of stellar structure (see, e.g. Shapiro & Teukolsky 1983) supplemented by the EOS yields the NS mass and radius against central density. The evolution of the interior temperature of an isolated NS is determined by the relativistic equations of energy balance and heat flux (see, e.g. Yakovlev & Pethick 2004b). Cas A NS cooling is simulated using the publicly available NSCool code (Page 2010), which, along with relativistic gravity, includes all the corresponding neutrino reactions, heat capacity, and thermal conductivity as functions of temperature, density, and composition of superdense matter in chemical equilibrium. The correct form (5) of the PBF energy losses was additionally incorporated.

3 COOLING SIMULATION

First, consider BSk25 EOS, which predicts the density threshold for direct Urca processes $n_{\text{Urca}} = 0.469$ fm$^{-3}$ (Pearson et al. 2018). It is reasonable to study the NS with a central density around this value.

The simulation result is demonstrated in Fig.1, which shows the cooling curves for neutron stars with masses 1.60$M_\odot$, 1.62$M_\odot$, and 1.65$M_\odot$. The upper panel shows the temporal behavior of the NS surface temperature (without gravitational redshift) on a small scale. It can be seen that, in the case of 1.65$M_\odot$, NS cooling occurs too quickly, which is caused by the participation of a large fraction of nucleon matter in direct Urca reactions. In the case of 1.60$M_\odot$ and 1.62$M_\odot$, the cooling trajectories pass through the current Cas A NS location, but they have a different slope at this point.

This is clearly seen in the lower panel, where these cooling trajectories are plotted on a large scale. The asterisks with error bars are the surface temperature of a neutron star in a supernova remnant Cassiopeia A, measured from the Chandra ACIS-S Graded spectra over the past 18 years, as reported in (Ho et al. 2021). (The surface temperature data were recalculated in accordance with the mass $M = 1.62M_\odot$ and radius $R = 12.36$ km of the simulated NS, assuming that $T_e^2 R = \text{const}$ at a fixed distance to the NS.) The thin dotted line represents the standard linear least squares fit showing the annual average rate of temperature change, and the gray area shows the 99% confidence interval for the Cas A NS surface temperature. It can be argued that during the observation period the effective surface temperature of the NS should be within the gray shaded area with a probability of 99%.

For $M = 1.60M_\odot$, the cooling trajectory does not fall within the confidence interval of 99%, demonstrating a stellar cooling rate below the observed one. In contrast, the cooling
curve corresponding to \( M = 1.62 M_⊙ \) shows excellent agreement with the observational data. This result is easy to understand if one remembers that the threshold of direct Urca processes for EOS BSk25 is \( M_{\text{th}} = 1.612 M_⊙ \). A NS with a mass \( M = 1.60 M_⊙ \) is below this threshold and cools through the emission of PBF neutrinos from its core according to the minimal cooling scenario. As discussed in the introduction, this cooling mechanism cannot provide energy losses consistent with the observed rate of temperature decrease. The NS mass \( M = 1.62 M_⊙ \) slightly exceeds the threshold, so direct Urca reactions are activated in a small part of the NS core, causing neutrino energy losses in addition to the PBF emission.

It should be noted that the part of nucleon matter where the direct Urca reactions are active has a very small mass \( \Delta M_{\text{Urca}} = 6.77 \times 10^{-3} M_⊙ \), and fills a small central volume with a radius \( R_{\text{Urca}} = 1.545 \times 10^7 \text{ m} \).

The neutrino luminosity from various neutrino sources inside the NS core is shown in Fig. 2 versus time. It can be seen that neutrinos from direct Urca reactions are not dominant in the energy losses, although they act immediately from the moment the neutron star is born. When the age of the NS reaches \( \sim 300 \text{ years} \) (the current age of the NS Cas A), a burst of PBF neutrinos is observed, which dominates the energy losses and causes the NS to cool rapidly. The next in the energy loss intensity during this period are direct Urca reactions, which additionally contribute to faster cooling.

For a better understanding of the hybrid cooling scenario, it is instructive to consider the temperature evolution inside the NS, which is shown in Fig. 3. It can be seen that in a small central volume with a radius of \( \sim R_{\text{Urca}} \) the temperature drops sharply and after \( \sim 10^{-4} \text{ years} \) is below the critical value for the triplet Cooper pairing of neutrons inside this volume. This causes the activation of PBF neutrino emission, but not strongly, because the volume of superfluid neutrons at this time is small. A small jump in the PBF energy losses occurs at the age \( 4.91 \times 10^{-1} \text{ years} \) owing to the expansion of the relatively cold region into a larger volume.

The luminosity of direct Urca reactions from the small volume is also not strong. The modified Urca processes dominate in the neutrino losses in the entire volume of the NS core until its complete cooling and the onset of neutron superfluidity, which occurs approximately after \( 10^2 \text{ years} \). At this time, the PBF neutrino emission from superfluid neutrons sharply increases and becomes dominant, causing rapid cooling, shown in Fig. 1.

The thermal soft X-ray spectrum of Cas A is in good agreement with the model of the carbon atmosphere (Page et al. 2011; Shternin et al. 2011). Light elements have a higher thermal conductivity and make the envelope more heat-transparent (Potekhin et al. 2003). Therefore, in addition to the NS model with an iron envelope, the model with a carbon envelope is of interest. According to the analysis of Shternin & Yakovlev (2015), a large amount of carbon in the envelope cannot be reconciled with the Cas A NS observations. Hence I have considered the case of a carbon layer with mass \( \Delta M = 10^{-10} M_⊙ \) that extends down from the atmosphere to the bottom of the NS envelope at \( \rho = 10^{10} \text{ g cm}^{-3} \). To relate the temperature \( T_e \) at the bottom of the heat blanketing envelope to its surface temperature \( T_s \), which is available for observations, I use the approximation for the \( T_e = T_s \) dependence in a carbon-iron envelope from (Beznogov et al. 2016). The best fit cooling trajectory for this case is shown in Fig. 4 together with the cooling curve for the NS

\[ T_e = T_s \]

\[ T_e = T_s \]

\[ T_e = T_s \]

\[ T_e = T_s \]
with iron envelope. Excellent agreement with observational data in this case is achieved by slightly varying the critical temperatures for neutron and proton superfluidity, as shown in Fig. 5.

Let us now consider the case of a NS built from BSk24 EOS. In this case, the density threshold for direct Urca processes is \( n_{dU} = 0.453 \text{ fm}^{-3} \), which corresponds to \( M_{dU} = 1.595M_\odot \) (Pearson et al. 2018), therefore, a NS with a mass \( M = 1.60M_\odot \) is the most suitable candidate for simulating the cooling of the Cas A NS. In such a star, the nucleon matter, where the direct Urca reactions are active, is concentrated in a central volume with a radius \( R_{dU} = 1.415 \times 10^5 \text{ m} \) and have a very small mass \( \Delta M_{dU} = 4.993 \times 10^{-3}M_\odot \). Thus, the cooling of the NS occurs according to the hybrid scenario. The cooling trajectory of such a star with iron and carbon envelopes is shown in Fig. 6. Excellent agreement with the observational data of Cas A NS in this case is also achieved with the aid of a small change in the critical temperatures for superfluidity of neutrons and protons.

4 DISCUSSION AND CONCLUSION

I propose a natural explanation for the observed stable rapid decrease in the surface temperature of the young Cas A NS, using the correct form of neutrino energy losses from the core of the superfluid NS, which is a well-known problem in the paradigm of minimal cooling. I draw the reader’s attention to the fact that the most recent EOSs: BSk24, BSk25 (Pearson et al. 2018), which have been accurately fitted to almost all available atomic mass data and are constrained to fit, down to the densities prevailing in the cores of neutron stars predict the activation threshold for direct Urca processes for NS with masses close to the most appropriate mass of the Cas A NS, following from observations. This fact suggests that the evolution of the Cas A NS does not fit into the minimal cooling paradigm.

To improve the Cas A NS cooling model I choose the NS mass so that the direct Urca processes are activated in a very small central volume of its core. In this case, a stable anomalous decrease in the NS surface temperature is provided by the combined losses of neutrinos from direct Urca reactions and the PBF neutrino emission that dominates in the current period.

As a reminder, the idea of the Cas A NS cooling owing to the direct Urca processes has already been expressed in (Taranto et al. 2016). Here, a scale factor has been used to significantly reduce the overall thermal conductivity to prevent cooling too quickly. The validity of this approach is highly questionable, since the lepton and nucleon thermal conductivities are known with good accuracy (see Shternin & Yakovlev 2007; Blaschke et al. 2012b, 2013).

On the contrary, the hybrid scenario of the Cas A NS cooling that I propose in this paper does not contain any adjustable parameters, except for a careful choice of the mass of NS and the generally accepted reasonable change in the critical temperature of nucleon pairing caused by the scatter in the results of numerous model calculations of the superfluid energy gap. This scenario unambiguously connects the used EOS and the mass of the NS, providing a new tool for processing observational data. The most suitable cooling trajectories for Cas A NS give the mass \( M = 1.62M_\odot \) and the
Figure 6. The best fit cooling trajectories for NS with a mass $M = 1.60M_\odot$ and a radius $R = 12.55$ km, with iron and carbon envelopes in comparison with data points from Ho et al. (2021).

radius $R = 12.36$ km using EOS BSk25 or $M = 1.60M_\odot$ and $R = 12.55$ km using EOS BSk24. The still existing large observational and theoretical uncertainties do not allow excluding other EOS. I have only shown that it is possible to accurately measure the mass of the NS using the method described.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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Hybrid cooling Cas A NS

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