Cooling neutron star in the Cassiopeia A supernova remnant: evidence for superfluidity in the core

Peter S. Shternin,1,2* Dmitry G. Yakovlev,1 Craig O. Heinke,3 Wynn C. G. Ho4* and Daniel J. Patnaude5

1 Ioffe Physical Technical Institute, Politekhnicheskaya 26, 194021 St Petersburg, Russia
2 St Petersburg State Polytechnical University, Politechnicheskaya 29, 195251 St Petersburg, Russia
3 Department of Physics, University of Alberta, Room 238 CEB, 11322-89 Avenue, Edmonton, AB T6G 2G7, Canada
4 School of Mathematics, University of Southampton, Southampton S017 1BI
5 Smithsonian Astrophysical Observatory, Cambridge, MA 02138, USA

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ABSTRACT
According to recent results of Ho & Heinke, the Cassiopeia A supernova remnant contains a young (∼330-yr-old) neutron star (NS) which has carbon atmosphere and shows notable decline of the effective surface temperature. We report a new (2010 November) Chandra observation which confirms the previously reported decline rate. The decline is naturally explained if neutrons have recently become superfluid (in triplet state) in the NS core, producing a splash of neutrino emission due to Cooper pair formation (CPF) process that currently accelerates the cooling. This scenario puts stringent constraints on poorly known properties of NS cores: on density dependence of the temperature $T_{cn}(\rho)$ for the onset of neutron superfluidity [$T_{cn}(\rho)$ should have a wide peak with maximum $\approx (7–9) \times 10^8$ K]; on the reduction factor $q$ of CPF process by collective effects in superfluid matter ($q > 0.4$) and on the intensity of neutrino emission before the onset of neutron superfluidity (30–100 times weaker than the standard modified Urca process). This is serious evidence for nucleon superfluidity in NS cores that comes from observations of cooling NSs.

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

1 INTRODUCTION
It is well known that neutron star (NS) cores contain superdense matter whose properties are still uncertain (see e.g. Haensel, Potekhin & Yakovlev 2007; Lattimer & Prakash 2007). One can explore these properties by studying the cooling of isolated NSs (see e.g. Pethick 1992; Yakovlev & Pethick 2004; Page, Geppert & Weber 2006; Page et al. 2009 for review).

We analyse observations of the NS in the supernova remnant Cassiopeia A (Cas A). The distance to the remnant is $d = 3.4^{+0.3}_{-0.2}$ kpc (Reed et al. 1995). The Cas A age is reliably estimated as $t \approx 330 \pm 20$ yr from observations of the remnant expansion (Fesen et al. 2006). The compact central source was identified in first light Chandra X-ray observations (Tananbaum 1999) and studied by Pavlov et al. (2000), Chakrabarty et al. (2001), and Pavlov & Luna (2009), but its nature has been uncertain. The fits of the observed X-ray spectrum with magnetized or non-magnetized hydrogen atmosphere models or with blackbody spectrum revealed too small size of the emission region (could be hotspots on NS surface although no pulsations have been observed, e.g. Pavlov & Luna 2009).

Recently Ho & Heinke (2009) have shown that the observed spectrum is successfully fitted taking a carbon atmosphere model with a low magnetic field ($B \lesssim 10^{11}$ G). The gravitational mass of the object, as inferred from the fits, is $M \approx 1.3–2.0 M_\odot$, circumferential radius $R \approx 8–15$ km and the non-redshifted effective surface temperature $T_\star \approx 2 \times 10^6$ K (Yakovlev et al. 2011). These parameters indicate that the compact source is an NS with the carbon atmosphere. It emits thermal radiation from the entire surface and has the surface temperature typical for an isolated NS. It is the youngest in the family of observed cooling NSs.

Yakovlev et al. (2011) compared these observations with the NS cooling theory. The authors concluded that the Cas A NS has already reached the stage of internal thermal relaxation. It cools via neutrino emission from the stellar core; its neutrino luminosity is not very different from that provided by the modified Urca process. Following Ho & Heinke (2009), Heinke & Ho (2010) analysed Chandra observations of the Cas A NS during 10 yr and found a steady decline of $T_\star$ by about 4 per cent. They interpret it as...
direct observation of Cas A NS cooling, the phenomenon which has never been observed before for any isolated NS. These results are confirmed by new observations we report below. We interpret them as a manifestation of neutron superfluidity in the Cas A NS.

When this Letter was nearly completed, we became aware of the paper by Page et al. (2010) who proposed similar explanation of the Cas A NS observations. However, the two papers are different in details and can be regarded as complementary. In particular, we discuss the dependence of cooling curves on the poorly known efficiency of neutrino emission due to Cooper pair formation (CPF) process and the possibility to interpret observations of all cooling stars by one model of superdense matter. It is important that we report the new observation.

2 NEW CHANDRA OBSERVATIONS

We use the Chandra data on the Cas A NS, discussed and fitted by Heinke & Ho (2010), and add one new data point. Briefly, the analysed data include the Chandra ACIS-S observations of Cas A longer than 5 ks. In order to ensure that all considered data are directly comparable, we take only the ‘directly comparable data’ of Heinke & Ho (2010). We exclude the subarray observation of Cas A (Patnaude & Luna 2009), since the pile-up properties (Davis 2001) of this spectrum differ from the others and those observations in which the Cas A NS dithered over bad pixels (most of the 2004 observations).

The new data point is produced from two ACIS-S observations of Cas A (Patnaude et al. 2010: ObsIDs 10936, 13177) taken on 2010 October 31 and 2010 November 2 for 33 and 17 ks respectively) and telemetered in GRADED mode (as done for previous Cas A observations). We used CIAO 4.2 and CALDB 4.2.1 to reprocess the data and produce response functions, correcting for the time-dependent ACIS quantum efficiency degradation and gain changes, but not for the charge-transfer inefficiency (as this cannot be mod-elled with GRADED data). We extracted source spectra with a 4-pixel (2.37 arcsec) radius region, and background spectra from an annulus of 5–8 pixels, as in Heinke & Ho (2010). We combined the two new observations in one set of spectra and responses (with an effective date of 2010 November 1) and grouped the spectrum by 200 count bin

We fitted these spectra simultaneously, forcing the NS mass and radius, along with the distance and hydrogen column density NH, to be the same as in the best fit of Heinke & Ho (2010) and Yakovlev et al. (2011), and finding the 1σ errors on the surface temperature at each epoch. This fitting is designed to cleanly define the relative variation in the temperature, separating this question from the absolute uncertainty in the temperature (described in detail in Yakovlev et al. 2011). The fitted values of the non-redshifted effective surface temperature $T_s$ (Table 1) are slightly different from those reported by Heinke & Ho (2010) for the 2004–09 observations, but within the 1σ errors. The key result is that the new observation confirms and extends the cooling trend seen in Heinke & Ho (2010).

3 SECOND TEMPERATURE DROP

The observed surface temperature decline is too steep and cannot be described by the theory discussed by Yakovlev et al. (2011; who did not analyse the decline itself). Heinke & Ho (2010) suggested that Cas A NS undergoes the last years of the internal crust–core relaxation accompanied by a pronounced surface temperature drop. However, the theory predicts (e.g. Lattimer et al. 1994; Gnedin, Yakovlev & Potekhin 2001; Yakovlev et al. 2011) a shorter relaxation, lasting typically $\lesssim 100$ yr. We propose another interpretation based on the effects of superfluidity in NS cores, in line with the work of Gusakov et al. (2004).

Neutrons, protons (and other baryons if present) in NS interiors can be superfluid (due to Cooper pairing). Free neutrons in the inner crust and protons in the core undergo Cooper pairing in spin-singlet state, while neutrons in the core can pair in spin-triplet state. Critical temperatures of superfluidity onset $T_c(\rho)$ are very model dependent (as reviewed e.g. by Page et al. 2004).

Our idea is that the initial crust–core relaxation in Cas A NS is over, leaving the star sufficiently warm. We assume further that not too strong triplet-state neutron superfluidity appeared in the core some time ago. It initiates a splash of neutrino emission due to CPF process producing the second $T_s$ drop that mimics the second (delayed) thermal relaxation. The second drop is mainly regulated by (i) the density dependence $T_c = T_c(\rho)$ of the critical temperature for the neutron pairing in the NS core, (ii) the reduction factor $q$ of CPF process by collective effects in superfluid matter and (iii) the neutrino luminosity prior to the onset of neutron superfluidity. These properties are very model dependent and poorly known but can be constrained from the Cas A NS observations.

The CPF process was first predicted by Flowers, Ruderman & Sutherland (1976) for singlet-state pairing neglecting collective superfluid effects. Collective effects can suppress the process $(q < 1)$ as was first noted by Leinson (2001) and calculated later by Leinson & Perez (2006), Sedrakian, Muther & Schuck (2007), Kolomeitsev & Voskresensky (2008), Steiner & Reddy (2009) and Leinson (2010); some discussion is also given by Page et al. (2009); the results are controversial. The main attention has been paid to CPF process due to singlet-state pairing of neutrons which has been found to be strongly suppressed $(q < 1)$. We are interested in triplet-state pairing in which case the suppression is thought to be less dramatic. If the latter CPF process were not affected by collective effects, then 24 per cent of neutrino emissivity would go through the vector weak interaction channel, while the rest (76 per cent) would go through the axial vector channel. Collective effects suppress the vector channel almost completely, but the axial vector channel survives. Exact value of $q$ is debatable (the lowest estimate $q \approx 0.19$ is given by Leinson 2010). Instead of relying on any specific model, we consider $q$ as a free parameter.

We illustrate this idea by cooling simulations of NSs with nucleon cores. We take the Akmal–Pandharipande–Ravenhall (APR) equation of state (EOS) in the core (Akmal, Pandharipande & Ravenhall 1998). By APR we mean the parametrization of APR results by

| Epoch (yr) | Exposure (ks) | $\log{T_s}$ (K) | ObsID(s) |
|-----------|---------------|-----------------|----------|
| 2000.08   | 50.56         | $6.325^{+0.0019}_{-0.0019}$ | 114      |
| 2002.10   | 50.3          | $6.327^{+0.0016}_{-0.0018}$ | 1952     |
| 2004.11   | 50.16         | $6.315^{+0.0019}_{-0.0019}$ | 5196     |
| 2007.93   | 50.35         | $6.310^{+0.0019}_{-0.0019}$ | 9117, 9773 |
| 2009.84   | 46.26         | $6.308^{+0.0019}_{-0.0018}$ | 10935, 12020 |
| 2010.83   | 49.49         | $6.306^{+0.0019}_{-0.0018}$ | 10936, 13177 |

Table 1. Carbon atmosphere spectral fits, using the best spectral fit $(M,R,d,N_{\text{HI}})$ of Heinke & Ho (2010) and Yakovlev et al. (2011), with the addition of 2010 data. Epoch dates are for the mid-points of the observations or weighted mid-points of merged data sets. Temperature errors are 1σ confidence for a single parameter.
Heiselberg & Hjorth-Jensen (1999) – the version APR I proposed by Gusakov et al. (2005). The maximum mass of a stable NS for this EOS is \( M_{\text{max}} = 1.929 M_\odot \); the powerful direct Urca process of neutrino emission is open in stars with \( M > M_{\text{DU}} = 1.829 M_\odot \). Let the direct Urca process and even less efficient modified Urca process be either not allowed or strongly suppressed in the Cas A NS. Otherwise, the star would be too cold after the initial crust–core relaxation; we would be unable to significantly speed up its cooling by the CPF process. To suppress Urca processes, we assume the presence of strong proton superfluidity in the core, with critical temperature \( T_{\text{cp}}(\rho) \gtrsim (2–3) \times 10^9 \text{ K} \); exact values of \( T_{\text{cp}} \) are unimportant. It occurs within a few days after the star formation. The proton CPF neutrino emission does not influence the cooling even if this emission were not affected by collective effects (e.g. Yakovlev et al. 2001). As long as neutrons are non-superfluid, the neutrino emission is mainly generated in neutron–neutron bremsstrahlung process. It is weak and leaves the Cas A NS sufficiently warm before the second temperature drop. Unless the contrary is indicated, we consider NSs with ordinary (non-accreted, non-magnetized) heat blanketing envelopes (e.g. Potekhin, Chabrier & Yakovlev 1997; Potekhin et al. 2003) and neglect superfluid effects in the stellar crust (which weakly affect the cooling after the crust–core relaxation; e.g. Yakovlev et al. 2001). Note, that a splash of CPF neutrinos makes the star slightly non-isothermal, with the cooling slightly dependent on the thermal conductivity in the core, but the isothermal state is soon restored.

Illustrative results are shown in Figs 1, 2 and 3. The left-hand panel of Fig. 1 gives three models of \( T_{\text{cn}}(\rho) \). We do not rely on any specific theoretical model but consider three phenomenological curves (a), (b) and (c) (locating neutron superfluidity at progressively lower densities). In our case, the maximum of \( T_{\text{cn}}(\rho) \) is strictly constrained to \( T_{\text{cn, max}} \approx (7–9) \times 10^8 \text{ K} \). Higher or lower \( T_{\text{cn}}(\rho) \) peaks would start the second temperature drop in the Cas A NS earlier or later than required by the observations (or even completely wash out this drop in a very young or old star). The \( T_{\text{cn}}(\rho) \) profiles should not be too narrow and the reduction factor \( q \) should

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**Figure 1.** Left-hand panel: models (a), (b) and (c) for critical temperature of triplet-state neutron pairing in NS core. Vertical dotted lines show central densities of NSs with \( M = 1 \) and \( 1.65 M_\odot \) (for APR EOS). Thin solid line is the temperature profile in the \( 1.65 M_\odot \) star of age 330 yr with neutron superfluidity (a). Right-hand panel: lines (a), (b) or (c) show cooling of the \( 1.65 M_\odot \) star with strong proton superfluidity and moderate neutron superfluidity (a), (b) or (c) in the core (\( q = 0.76 \)) compared with observations of Cas A NS cooling. The dotted line is the same for the \( 1.75 M_\odot \) star and neutron superfluidity (a). The line (a) for \( M = 1.65 M_\odot \) is also shown in the inset over longer time-span. Lines pSF and N in the inset are calculated for \( M = 1.65 M_\odot \) neglecting, respectively, neutron superfluidity and entire nucleon superfluidity in the core.

**Figure 2.** Sequences of (solid) cooling curves for NSs of masses from \( 1 M_\odot \) to \( M_{\text{max}} \) (through \( 0.1 M_\odot \)) with strong proton superfluidity and moderate neutron superfluidity (a) (left-hand panel) or (c) (right-hand panel) in the core (\( q = 0.76 \)) compared with observations of isolated NSs. Dashed lines refer to warmest stars of these types – \( 1 M_\odot \) stars with the carbon surface layer of mass \( 10^{-8} M_\odot \). Dot–dashed lines refer to coolest \( M_{\text{max}} \) stars without proton superfluidity in the inner core.

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not be too small (otherwise, the second temperature drop would be weak). Other plots give theoretical cooling curves $T_\alpha(t)$ (i.e. the redshifted surface temperature versus $t$).

The right-hand panel of Fig. 1 gives three cooling curves for the $1.65 M_\odot$ star of nearly Cas A NS age with $T_{\alpha}(\rho)$ models (a)–(c) from the left-hand panel and with $q = 0.76$ (axial vector channel is not suppressed). The curves are compared with the Cas A NS data. All three superfluidity models agree with these data. Taking superfluidity (a) and increasing the stellar mass to $1.75 M_\odot$ makes the CPF process more important and starts the second temperature drop earlier (the dotted curve), in disagreement with the data. However, we could easily readjust (slightly decrease) $T_{\alpha}(\rho)$ and explain the Cas A NS data with the $1.75 M_\odot$ model. Therefore, we can successfully fit the data for a range of NS masses and take the $1.65 M_\odot$ star as an example. The inset shows the cooling curve (a) ($M = 1.65 M_\odot$) over longer time-scale. The second temperature drop at $t \sim 250$ yr is clearly pronounced here. Also, we show the cooling of non-superfluid star (curve N) and the star with proton superfluidity alone (curve pSF). Without the CPF process, the slopes of both curves are much smaller than required.

In Fig. 2, we test two neutron superfluidity models, (a) and (c), against observations of other isolated NSs. Observational data are taken from references cited in Yakovlev et al. (2008) and Kaminker et al. (2009) with the exception of PSR J0007+7303. The data on the latter source are taken from Caraveo et al. (2010) and Lin et al. (2010). Note that in fig. 5 of Yakovlev et al. (2011), similar to Fig. 2, source labels 12, 13 and 14 should refer to RX J1856–3754, Geminga and PSR B1055–52, respectively.

We make a reasonable assumption that all NSs have different masses but the same physics of matter in their cores. We present cooling curves (solid lines) for a number of masses (from top to bottom), from $1 M_\odot$ to $M_{\text{max}}$. Recall, that we use the model of strong proton superfluidity in the entire core that switches off Urca processes in all stars. With this assumption, neutron superfluidity (a) allows us to explain almost all sources, except for warmest and coolest ones (for their ages). However, neutron superfluidity (c) produces too strong CPF neutrino emission in low-mass stars and cannot explain the majority of warmer stars although it agrees with the Cas A NS data.

Furthermore, we can raise the cooling curves of low-mass, not too old NSs assuming they have more heat-transparent heat-blanketing envelopes of light elements. For example, the dashed curves in Fig. 2 are calculated for $M = 1 M_\odot$ NS with the carbon envelope of mass $10^{-8} M_\odot$. We can also lower the cooling curves of massive ($M_{\text{max}}$) stars: the dot–dashed lines are computed by taking more realistic models for proton superfluidity, with $T_{\alpha}(\rho)$ going down at high densities. This opens direct Urca process in the inner core and gives coldest possible NSs. Therefore, we can really explain all the data with superfluidity (a), but not with superfluidity (c).

The second temperature drop is known in the NS cooling theory (e.g. Kaminker, Haensel & Yakovlev 2001). Cooling models like (a) and (c) in Fig. 2 have been analysed by Gusakov et al. (2004) with the same conclusion that models like (a) can explain observations of all isolated NSs. Similar models of NSs with nucleon cores, where direct Urca is forbidden but CPF operates, were used as the basis of the minimal cooling theory (Page et al. 2004, 2006, 2009) although that theory employs selected $T_{\alpha}(\rho)$ profiles, most favourable by the theory of nucleon superfluidity. Now we see that the model of Gusakov et al. (2004) is also suitable to explain the Cas A NS data.

Finally, Fig. 3 demonstrates the effect of suppression of CPF neutrino emission in the axial vector channel. To maximize the CPF emission, we take constant $q_{\alpha}$ over the core. It produces especially strong splash of CPF neutrinos when the second temperature drop starts. Three solid lines are the cooling curves for the $1.65 M_\odot$ star calculated at $q = 0.7, 0.4$ and 0.19. Otherwise, the conditions are the same as in the right-hand panel of Fig. 1. With our constant $T_{\alpha}$, CPF neutrino emission at $q = 0.7$ is too strong; it gives faster Cas A NS cooling than required by observations. The case $q = 0.4$ now agrees with the observations. Smaller $q = 0.19$ gives slower cooling that cannot explain the data. Note that the $T_{\alpha}$ = constant model is hardly realistic. For more realistic $T_{\alpha}(\rho)$ profiles, we can reconcile theory with the Cas A NS data at $q > 0.4$. This gives a useful restriction on the uncertain theoretical parameter $q$.

In the inset of Fig. 3, we show the same three cooling curves over larger range of ages. In addition, we plot the same dashed line for non-superfluid star as in the right-hand panel of Fig. 1, and another dot–dashed line for the star with neutron superfluidity alone with $T_{\alpha} = 4.3 \times 10^8$ K and $q = 0.76$. The latter superfluidity triggers a splash of CPF neutrinos, but the main modified Urca neutrino emission is too strong and the splash cannot produce a steep $T_\alpha$ decline required by the observations. Adding a carbon surface layer of mass $\sim 10^{-12} M_\odot$, we could raise the latter curve to the Cas A NS level but would be unable to reproduce the cooling slope. Our calculations show that the modified Urca emission should be suppressed at least by a factor of 30 (for the most efficient CPF emission with $q = 0.76$ and constant $T_{\alpha}$) to get the required slope. Taking smaller $q$ or narrower $T_{\alpha}(\rho)$ profile would require stronger suppression of the modified Urca process.

**4 CONCLUSIONS**

We report a new (2010 November) Chandra observation of the young Cas A NS that confirms the observed (Heinke & Ho 2010) steady decline of the surface temperature $T_\alpha$ (by 4 per cent over 10 yr). We propose a natural explanation of the observed decline. We assume that the Cas A NS underwent the traditional internal crust–core relaxation some time ago and now demonstrates the second temperature drop due to the onset of triplet-state neutron superfluidity in its core and associated neutrino emission. We can explain the Cas A NS observations under the following conditions.

![Figure 3. Same as on the right-hand panel of Fig. 1 but for constant $T_{\alpha}$ over the core at three values $q = 0.19$ ($T_{\alpha} = 7.55 \times 10^8$ K), 0.4 ($7.2 \times 10^8$ K) and 0.7 ($7 \times 10^8$ K). The inset shows the same cooling curves but over larger range of ages, together with the dashed curve for non-superfluid star and the dot–dashed curve for the star without proton superfluidity but with neutron superfluidity at $T_{\alpha} = 4.3 \times 10^8$ K.](https://www.researchgate.net/publication/303727762_Cooling_Cas_A neutron_star)
(i) The maximum critical temperature for triplet-state pairing of neutrons should be $T_{c\text{,max}} \approx (7-9) \times 10^8$ K. Otherwise, the second temperature drop occurs earlier or later than required by observations.

(ii) The $T_{c\rho}(\rho)$ profile over the NS core should be rather wide for the CPF neutrino emission to gain enough strength.

(iii) For the same reason, the suppression of the CPF process by collective effects cannot be too strong ($q > 0.4$).

(iv) The neutrino emission of the star before the second temperature drop should be 30–100 times lower than due to the modified Urca process (e.g. the modified Urca can be suppressed by strong proton superfluidity). Otherwise, the second temperature drop would not be pronounced.

When these criteria are met, we can still locate $T_{c\rho}(\rho)$ profiles in different parts of the NS core. If, however, we wish to explain all current observations of isolated NSs with one and the same $T_{c\rho}(\rho)$ profile, we will be forced to push this profile deeper in the core (Fig. 2). Alternatively, we could employ broader profiles but with density-dependent factor $q$ (which can increase within the core as for singlet-state pairing, e.g. Kolomeitsev & Voskresensky 2008). This would shift the efficiency of the CPF process to higher $\rho$ in superfluid matter.

We have taken one EOS and focused on 1.65 $M_\odot$ neutron star model, but our basic conclusions will not change for a large variety of EOSs and masses $M$. For instance, taking the same EOS we have considered the Cas A NS models with $M$ from 1.4 to 1.9 $M_\odot$. By slightly changing $T_{c\rho}(\rho)$ profiles, we are able to explain the data for any $M$ from this range.

Our calculations indicate that the second temperature drop lasts for a few tens of years and Cas A NS is at its active CPF neutrino emission stage. These models would be inconsistent with a sharp stop of the temperature decline in a few years, which can be verified with future observations.

After the second temperature drop, the Cas A NS is expected to become a rather cold slowly cooling NS.

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