

Thermal Evolution of Hyperon-Mixed Neutron Stars with Updated Equation of State

Katherine Bruce; Sachiko Tsuruta; Andrew C. Liebmann; Marcus Teter; Madeline Kelly; Ken'ichi Nomoto

Accessibility Disclaimer:

For a more accessible version of this document, please submit an accessibility request form through the Montana State University Library website.

Thermal Evolution of Hyperon-Mixed Neutron Stars with Updated Equation of State

Katherine Bruce^{1,*}, Sachiko Tsuruta^{1,2}, Andrew C. Liebmann¹, Marcus Teter^{1,3}, Madeline Kelly¹, and Ken'ichi Nomoto²

¹Department of Physics, Montana State University, 1325 S 6th Ave, Bozeman, MT 59717, USA

²Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8583, Japan

³RTX, 16510 E. Hughes Dr., Aurora, CO 80011, USA

Received November 13, 2025; Revised March 23, 2026; Accepted March 24, 2026; Published April 15, 2026

.....
The presence of hyperons in neutron stars allows the star to cool via the hyperon direct Urca process, which can release energy from the star faster than the standard modified Urca process. Previous cooling calculations verified that hyperons can exist in the core of neutron stars and facilitate direct Urca cooling. In the current article, we first update the observational data on the thermal evolution of neutron stars. Then, adopting the latest realistic equation of state for hyperon-mixed neutron stars, the cooling of these stars is calculated, and the results are compared with the most recently updated observational data. The results confirm that the hyperon scenario can explain the thermal evolution of all observed stars, including the faster cooling of some of these stars if their fast cooling is substantially suppressed due to the presence of hyperon superfluidity in moderately massive stars.
.....

Subject Index E11, E32

1. Introduction

The first neutron star (NS) cooling calculations [1] showed that NSs can be visible as X-ray sources for about a million years. After a supernova explosion, a newly formed NS first cools via various neutrino emission mechanisms before the surface photon radiation takes over. The launch of the *Einstein Observatory* gave the first hope of detecting thermal radiation directly from the surface of NSs. However, the temperatures obtained by the *Einstein* were only the upper limits. *ROSAT* offered the first confirmed detections (not just upper limits) for such surface thermal radiation from at least three cooling NSs: PSR B0656+14, PSR J0633+1746 (Geminga), and PSR B1055-52 [2].

More recently, the prospect for measuring the surface temperature of isolated NSs, as well as obtaining better upper limits, has increased tremendously, thanks to the abundant superior X-ray data from *Chandra*, *XMM-Newton*, *XRISM*, etc., as well as the data in the lower energy bands from optical–UV telescopes such as the *Hubble Space Telescope* (HST). Consequently, the number of possible surface temperature detections for isolated NSs has increased tremendously. These developments have proven to offer serious “turning points” for the detectability of thermal radiation directly from the surface of NSs, because we can now seriously compare the observed temperatures with NS cooling theories; see, e.g. Ref. [3].

*katherinebruce@montana.edu

NS temperature observations are very important because they can probe various physical properties of NSs. For example, they can examine the composition and the quantum state (e.g. superfluidity, superconductivity, etc.) of some of the constituent particles, which are hard to examine directly (see, e.g. Ref. [4]).

Many NSs cool by the standard neutrino cooling process, such as the modified Urca process and the bremsstrahlung process; see, e.g. Ref. [1]. However, some cooler NSs cool faster, and they require a faster direct Urca process, which is modified by, e.g. the superfluidity of the constituent particles [5]. There are various such direct Urca processes (see Section 2.2). The direct Urca process with hyperons is one of these possibilities. The direct Urca cooling for stars with a hyperon-mixed core was examined in our recent paper [3]. The current paper further examines the hyperon direct Urca cooling, which is a continuation of the earlier paper [3]. There are three major motivations for carrying out the current studies as a follow-up.

(i) In our recent paper [3], where the hyperon direct Urca was used, we adopted the TNI6U equation of state (EOS) model, where the maximum mass of the star gets up to $1.8M_{\odot}$. However, since then Ref. [6] showed that the maximum mass of an NS gets up to near $2M_{\odot}$. One major motivation of the current paper is to improve our model by adopting a new EOS, TNI8U, whose maximum mass is $2.1M_{\odot}$.

(ii) Another motivation of the current paper is that the new model TNI8U adopted not only produces the required higher stellar mass stars, but also it is more physically relevant because the new EOS TNI8U adopts a more universal approach, where the many-body force extends to all constituent particles, including hyperons. In the TNI6U model adopted in Ref. [3], the many-body force applies only to nucleons.

(iii) The third motivation of this paper is the significant improvement on the observation data themselves. So far, the observation data adopted in all published papers have not been uniformly organized and not been up to date. In our current effort, for the first time, to our knowledge, a considerable amount of time has been spent, with special care, to examine all currently up-to-date observation data on isolated NSs, and the results are presented in Table A1, and they are compared with the recently published earlier data (see Sections 3, 4, and 5).

After the introduction in Section 1, we present in Section 2 the thermal evolution model adopted, and Section 3 introduces the updated observational data. Section 4 presents the results, which are compared with the up-to-date observation data. The discussion follows in Section 5, and the conclusion is given in Section 6.

2. Thermal evolution model

In the first detailed calculations for the NS model in Ref. [1], the isothermal approximation was applied, where a set of basic stellar structure-evolution equations is divided into the first two equations for the stellar structure and the last two for the stellar evolution and energy transport. Soon after the first NS was discovered, the first numerical basic general relativistic stellar structure-evolution code was constructed, where the whole set of stellar structure-evolution equations is solved simultaneously without making the isothermal approximation; see, e.g. Ref. [5]. We refer to this code, for convenience, as “the exact neutron star evolution code.” Since then, over the years, this code has been refined and improved continuously. Consult with the abundant already published general and review papers, listed, e.g. in Refs. [7,8], and [5], for the details.

In our current calculations, we adopt the latest version of our exact NS structure-evolution code, which consists of the first two relativistic Tolman–Oppenheimer–Volkoff structure equations, and the relativistic version of the last two, for the stellar evolution and the energy transport. The structure equations are integrated considering the radiative and conductive opacity, neutrino luminosity, photon luminosity, etc., at each time-step in the evolutionary sequence.

In order to solve our exact evolutionary code for studying the nature of NS thermal evolution, several ingredients, such as the physical input, are required. In the following subsections, we summarize the basic physics involved. In our NS thermal evolution code, we currently utilize the most up-to-date version.

2.1. EOS

Among the important input physics, the outstanding one is the EOS, $P = P(X, \rho, T)$, where X is the composition, ρ is the energy density including both kinetic and potential energy, and T is temperature. This equation depends heavily on the strong force among constituent particles.

A “soft” EOS includes a strong attractive nuclear force between particles, creating a lower mass and denser star, whereas a “stiff” EOS includes stronger repulsive forces, leading to higher-mass stars with a lower central density.

Earlier, the inclusion of hyperons in NS cores led to EOS that were too soft to produce stars comparable to observations. That problem was solved, e.g. in the new EOS created by the Takatsuka group, TNI6U and TNI8U [9], and in the current article, these EOS are used. These EOS adopt the many-body force approach. In the latest TNI8U adopted in the current article, the Universal many-body approach is used. In our earlier EOS TNI6U used in Ref. [3], the two-body nuclear force was applied only among nucleons. However, in the new TNI8U, the many-body force is applied to all constituent particles, including both hyperons and nucleons, not just nucleons. The adoption of the earlier TNI6U EOS led to a maximum stellar mass of $1.8M_{\odot}$, which is lower than the mass of a newly observed NS with $1.97M_{\odot}$ [6]. With the new TNI8U EOS adopted in the current paper, the maximum mass reaches $2.1M_{\odot}$. In this new EOS TNI8U, the strong many-body force acts universally among all constituent particles, including hyperons, not just among nucleons [9]. This additional repulsive force makes the EOS stiff enough to produce stars massive enough to include the new upper mass limit.

In Fig. 1, the pressure vs. energy density relation is shown for both the TNI6U and TNI8U models. We see that both curves are approximately similar until about the nuclear density, but, as expected, TNI8U gets somewhat stiffer and higher beyond that density. The difference gets larger as the density increases. That results in the stellar mass reaching the required maximum mass for TNI8U.

The properties of stars generated with our two EOS, TNI6U and TNI8U, are shown in Table 1.

Comparing these two cases for the same effective masses M_p of, e.g. $1.4M_{\odot}$ and $1.6M_{\odot}$, we clearly see that TNI8U has a larger radius R , lower central density ρ_m^c , and lower pressure P^c . The stellar radius is 11.778–11.364 km for TNI8U and 11.162–10.350 km for TNI6U. These values are already expected from the earlier works [1], because both of these EOS are more or less of a typical medium range.

2.2. Neutrino emission

In general, during the earlier hot stages, NSs cool by neutrino emissions, but then at an age of about 10^{5-6} years, when the star becomes cooler, the luminosity of photons emitted from the

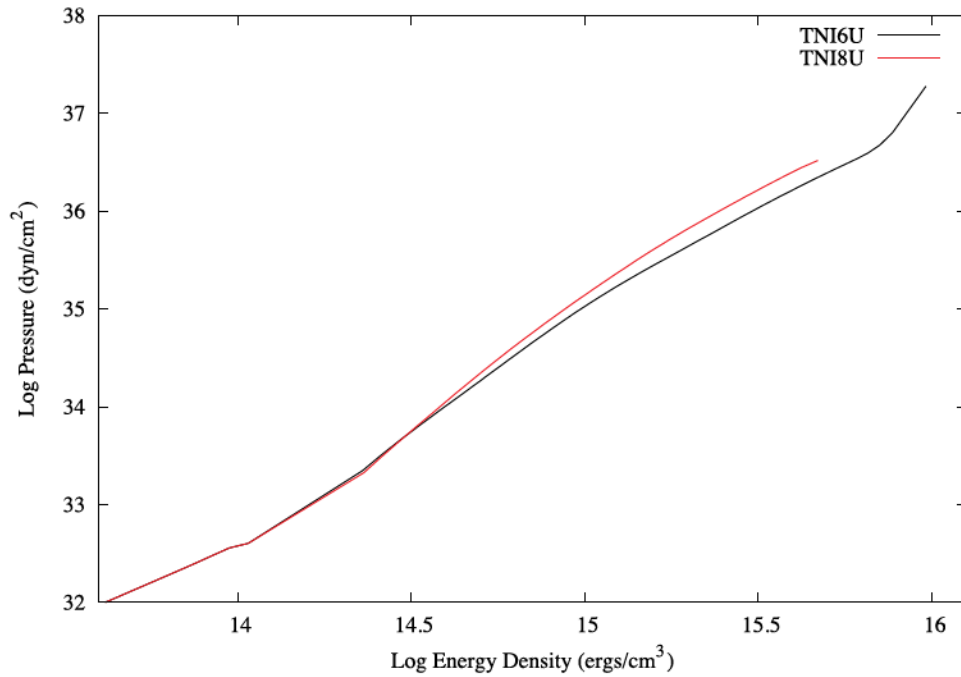


Fig. 1. Log energy density versus log pressure for TNI6U (black) and TNI8U (red). For energy densities below 10^{14} ergs/cm³, the EOS are the same.

Table 1. Properties of EOS models TNI6U and TNI8U. Notes: R [km], R_e [km], M_p [$M_\odot$], ρ_m^c [g/cm³], ϵ^c [g/cm³], and P^c [dyne/cm²] are stellar radius, effective radius, proper (baryonic) mass, central baryon matter density, central energy density, and pressure, respectively.

EOS	R	R_e	M_p	$\log(\rho_m^c)$	$\log(\epsilon^c)$	$\log(P^c)$
TNI8U	11.778	14.171	1.4	14.936	14.924	34.981
	11.750	14.342	1.5	14.962	14.964	35.045
	11.706	14.504	1.6	14.987	14.984	35.110
	11.665	14.672	1.7	15.013	15.014	35.174
	11.611	14.833	1.8	15.040	15.048	35.237
	11.536	14.983	1.9	15.034	15.074	35.303
	11.461	15.135	2.0	15.094	15.094	35.368
	11.364	15.277	2.1	15.123	15.124	35.436
TNI6U	11.162	13.675	1.4	15.018	15.060	35.155
	10.911	13.904	1.6	15.093	15.140	35.338
	10.867	13.937	1.63	15.106	15.159	35.367
	10.800	13.976	1.67	15.123	15.180	34.409
	10.676	14.019	1.73	15.152	15.214	35.476
	10.633	14.034	1.75	15.162	15.226	35.500
	10.610	14.041	1.76	15.167	15.230	35.512
	10.350	14.101	1.85	15.290	15.451	35.782

stellar surface begins to dominate. The neutrino luminosity is much stronger than any other emission process at high temperatures, explaining its dominance in the earlier stages of cooling. Both processes depend on temperature, so as the star cools, the efficiency of neutrino cooling

drops and photon cooling takes over. See, e.g., Ref. [10], and the most recent review in Ref. [5], for further details.

The neutrino cooling era is the most important during the earlier stages, where the neutrino emission could be due to either a standard or a nonstandard process. The Pauli exclusion principle prohibits direct Urca cooling from happening with plain neutron matter [11], unless the proton fraction is high enough. This leads to the modified Urca process. However, in various other cases, the faster direct Urca process is possible, e.g., the direct Urca involving various hyperons [7, 8], etc.), those involving quarks, kaon condensates, pion condensates, etc. The details are found in, e.g., Ref. [8] and the more recent review paper [5].

The earlier calculations have used slower neutrino cooling mechanisms such as modified Urca, plasmon, and bremsstrahlung processes, usually referred to as “standard” cooling mechanisms. Many stars observed are consistent with the standard cooling, but some stars cool faster (see Sections 3 and 4). These stars require faster cooling. With the presence of exotic particles, much faster “nonstandard” cooling mechanisms can occur. There are various processes where that takes place. The hyperon direct Urca is one possibility.

In this paper, we adopt the hyperon-mixed stars where the hyperon direct Urca process is possible. For both $^{\text{TM}}\text{NI6U}$ and $^{\text{TM}}\text{NI8U}$, the small NS radius (see Table 1) leads to a low proton fraction, below the threshold of $1/9$ required for the nucleon direct Urca process [11]. As a result, there must be an alternative fast cooling process to explain some cold NS observations [12]. In these EOS, if the density becomes high enough, then hyperons can be present in the core. This leads to fast cooling via the hyperon direct Urca cooling process for stars with $M \sim 1.9 M_{\odot}$ and heavier. The current paper is the continuation of Ref. [3], which first investigated the possibility of the hyperon direct Urca cooling process. We adopt the modified nucleon Urca process and other standard processes for less massive stars in the absence of hyperons, whereas all the hyperon direct Urca processes are used in more massive stars with the hyperon-mixed core.

2.3. Effect of Superfluidity

Once the core temperature of the star falls below the critical temperature for superfluidity of a constituent particle T_c , the particle becomes superfluid.

Figure 2 shows the density dependence of superfluid critical temperature T_c , where n and p refer to neutron and proton, and the rest are various kinds of hyperons. The one-pion-exchange potential (OPE) σ -B model is for nucleons, whereas the σ hime model is for hyperons. The $^{\text{TM}}\text{NI6U}$ model is adopted to obtain Fig. 2, but it is usable for the qualitative discussion of our $^{\text{TM}}\text{NI8U}$ model also, because the superfluid property of these models is quite similar.

The superfluidity of a particle leads to suppression of its neutrino emission when the temperature T becomes below the critical superfluid temperature T_c , and that causes the star to cool more slowly. Specifically, when T gets below T_c , the luminosity decreases roughly exponentially as T/T_c [3, 5].

As the star cools after the formation by a supernova explosion and the interior temperature falls below the superfluid critical temperature, T_c , some constituent particles become superfluid. That causes suppression of both specific heat and hence the internal energy and all neutrino processes involving these particles. The net effect is that the star cools more slowly (and hence the surface temperature and luminosity will be higher) during the earlier neutrino cooling era.

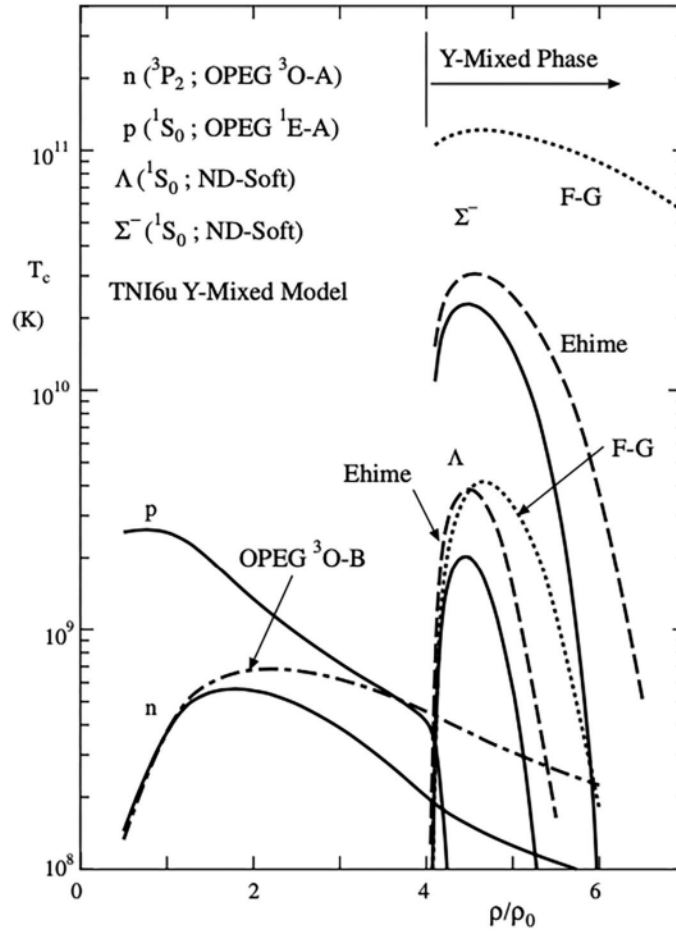


Fig. 2. Density dependence of critical temperature for various superfluid models, taken from Ref. [3]. ND: Nijmegen-D; F-G: Funabashi-Gifu.

2.4. Opacity

In the central core of an NS, the conductivity of the constituent particles (protons, neutrons, hyperons, etc.) is so high that the stellar core is essentially isothermal. The surrounding crust just outside the core consists of highly neutron-rich heavy nuclei, free neutrons, and electrons with high conductivity. However, in the crust closer to the surface, free neutrons disappear, and the heavy nuclei are less contaminated by neutrons. In this area, both radiative and conductive opacity can operate, depending on the temperature [1,3].

2.5. Composition

The composition of the matter in the NS cores is predominantly neutrons with a small fraction of protons, electrons, and muons if the density is moderate $(0.6\text{--}1)\times 10^{15} \text{ g cm}^{-3}$. For higher densities, hyperon contamination, pion condensation, kaon condensation, and the quark de-confined phase may appear in the inner central core, while NS matter will remain in the outermost region of the core.

The central core is surrounded by the inner and outer crusts. The inner crust consists of free neutrons, electrons, and neutron-rich heavy nuclei, while the outer crust consists of heavy nuclei and electrons. Right after the supernova explosion, light elements, such as hydrogen

and helium, may fall onto the surface, and then the atmosphere and crust may be contaminated with some amount of these light elements (see, e.g. Ref. [13]). In that case, due to higher conductivity with these light elements, the surface temperature becomes higher for a given internal temperature, which is determined by neutrino cooling in the earlier stages of thermal evolution. Then the cooling curves (the surface temperature versus age relation) will be higher than without these light elements during the neutrino cooling era, but the trend is reversed in the later photon cooling era. The light element contamination is expected for younger stars, but these light elements are expected to go through nuclear burning to heavier elements in time (see, e.g. Ref. [14]). Therefore, it is expected that this will not be the case for older stars.

The equilibrium composition of NS atmospheres is one of heavy elements peaking at the ordinary terrestrial stable iron (Fe) (e.g. Refs. [1,7]). However, the fallback light elements, such as H and He, may remain in the atmospheres of younger stars, which will seriously affect the estimation of the surface temperature from the observed data. This is because whereas the continuum spectrum with the Fe atmosphere mimics a blackbody, the spectrum is very different from a blackbody for the atmosphere with light elements such as H. The net effect is that the same observational data will result in lower surface temperatures for hydrogen atmospheres than for a blackbody (e.g. Ref. [15]).

Further details of the basic physics involved in the NS composition problem are found, e.g. in Refs. [1,7].

3. Observation

Since the first detection of a NS by *ROSAT*, many isolated NSs have been discovered by subsequent advanced X-ray missions (see, e.g. Ref. [3] for the details).

Most recently, we reexamined all the currently existing data of observed isolated NSs. Table A1 in the Appendix presents the results, as NS age versus luminosity, with the reference adopted also listed.

The table compares the data on the sources given in the 2009 hyperon paper [3] (the 5th and the 6th columns) with the data on the sources in the current 2026 paper (the 2nd to the 4th columns).

Beyond the updated age of 3C 58, PSR 1706 has had a significant revision in its luminosity that has resulted in a lower total luminosity as well as a smaller range of errors. There are some minor revisions to Vela's age and luminosity. It is established that Cas A and PSR B2334 have had lower limits on their luminosities, and there is a minor update on the age of PSR B0656. It is important to compare the current curves of the Vela-like sources, 3C 58, PSR 1706, and PSR 2334, in addition to Vela itself, with their earlier results in the 2009 paper in Ref. [3].

Additionally, there are 14 new sources that are included in the 2026 data, which were not in the 2009 data. They include another Vela-like object: Vela Jr. There are also two sources that were in the 2009 paper, PSR J1509 and PSR J0154, which are now classified as high magnetic pulsars, and hence they are not included in Fig. 3.

4. Results

The thermal evolution of hyperon-mixed NSs was calculated for stars with various mass values, and the results are shown in Fig. 3, which are compared with the most recent observational data reported in Table A1.

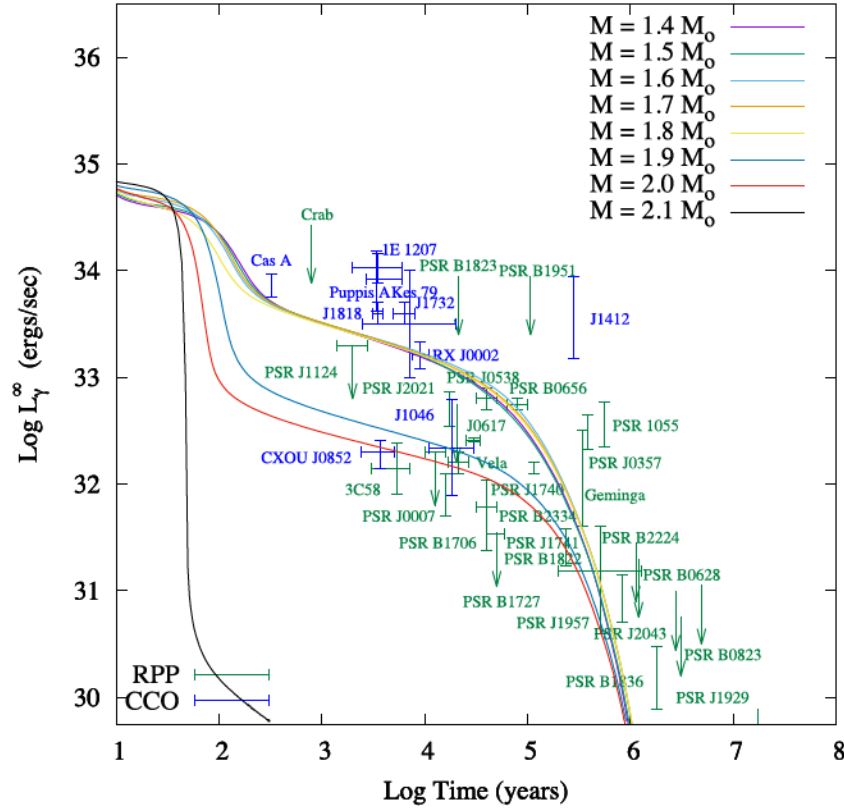


Fig. 3. Thermal evolution of NSs. RPP represents rotation-powered pulsars, whereas CCO refers to the central compact objects. The vertical bar is the detection, whereas the downward arrow is the upper limit. See Table A1 for the data.

For the stars with masses in the lower range of 1.4 through $1.8M_{\odot}$, the density of the core is lower than the transition density above which hyperons appear. Therefore, they are composed of only neutron matter, and they go through the standard cooling.

The bottom three curves are for heavier, denser stars with masses of 1.9 , 2.0 , and $2.1M_{\odot}$. Their core density exceeds the threshold density where the Λ and Σ hyperons appear, and hence it consists of these hyperons, and the central core emits neutrinos with the fast hyperon direct Urca process, and hence these stars cool more quickly. However, depending on their density, this fast cooling can be suppressed if the constituent particles are in a superfluid state, which depends on density, as shown in Fig. 2, where the density dependence of the superfluid critical temperature T_c is shown. The suppression goes roughly exponentially as T/T_c when temperature T gets less than T_c . So when T is below T_c , the fast cooling is suppressed. The heaviest star with $M = 2.1M_{\odot}$ is the fastest by far, because the core density is high enough so that the stellar temperature T is high enough compared with T_c , which decreases sharply at higher densities (see Fig. 2). Therefore, the suppression does not take place, and the star cools very fast. On the other hand, the intermediate-mass stars with $M = 1.9M_{\odot}$ and $2.0M_{\odot}$ are less dense, and T gets below T_c , and hence their core is in the superfluid state. For this density range, significant superfluid suppression is therefore effective and hence fast cooling is significantly reduced (see Fig. 3).

We note that many stars (e.g. RX J0002, PSR J0538, PSR B0656) are consistent with the standard cooling, but some others (e.g. Vela, PSR J0852, PSR B1706, PSR J1746) require the faster

nonstandard cooling with some degree of suppression. A few detection points (e.g. 1E1207) are above the standard cooling curves shown in Fig. 3. The curves shown in Fig. 3 are obtained for stars with cooling without heating. With additional heating, the star cools more slowly (see Ref. [3]). Also, whereas our models consist of standard stellar crusts with heavy elements, if the stellar crusts are contaminated by light elements such as hydrogen, the star cools more slowly and hence appears hotter (see Section 2.5 and Ref. [14]). Our models are consistent with observation when in these stars, these additional factors are in operation.

5. Discussion

Only a few of the stars reported here, e.g. Crab, Cas A, and 3C 58, are generally considered to be historical objects. The age of the rest of the stars has been estimated mostly by the usual spin-down rate method or sometimes by the expansion rate of the leftover supernova remnant (see Ref. [3]).

Before 2013, 3C58 was thought to be SN 1181, a historical object about ~ 850 years old [16]. However, SNR Pa 30, recently discovered, which is not a historical object, appears to be a better candidate for 3C58 [17]. Given that 3C58 is now unlikely to be associated with a historical event, the spin-down age ($\log_{10} t = 3.792$) and optical and radio expansion ages are now the most consistent age estimate for 3C58. However, that uncertainty will not change the conclusion reached in the current paper. The differences between the historical age and the spin-down age are somewhat different for Crab and Cas A, but the difference is very small, and that also does not change the conclusion of the current paper.

Well-established lower limits have been found for 3C58, CXOU J0852, and PSR B2334 [18], and we can say that these stars are a class of NS with Vela as the prototype. These “Vela-like” objects are middle-aged, at the 1000–10 000 years level, and they are cool for their age, with $\log_{10} L < 32.4$ ergs s^{-1} . In order to explain their cooling, a heavier stellar mass, with $1.9\text{--}2.0 M_{\odot}$, is needed. With higher masses, more hyperons appear in the core, which cools the star faster, whereas with smaller masses, fewer hyperons appear and the star cools more slowly. However, this mass window is relatively small. There are others that likely fit into this class, but their measured luminosities are too large or lack a lower limit to be considered at this time.

6. Conclusion

We carried out cooling calculations for hyperon-mixed NSs using the exact thermal evolution code, adopting a new realistic EOS involving the Universal many-body approach. The results are compared with updated observational data. The conclusion is that many less massive stars cool with the standard neutrino process, whereas some other more massive stars require a faster nonstandard neutrino process, such as the hyperon direct Urca process, which is to be reduced significantly by the superfluid suppression.

Funding

This work received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data Availability

The data underlying this article are available in previously published articles and publicly accessible archives, as cited in this manuscript. No new data were generated.

Acknowledgements

S.T. thanks IPMU for hospitality. S.T. also acknowledges with thanks Drs. Tamagaki and Takatsuka for providing the details of their new Universal equation of state.

Appendix. Observational data

References

- [1] S. Tsuruta, Neutron star models, PhD thesis (Columbia University, New York, 1964).
- [2] W. Becker, *Ann. N. Y. Acad. Sci.* **759**, 250 (1995).
- [3] S. Tsuruta, J. Sadino, A. Kobelski, M. A. Teter, A. C. Liebmann, T. Takatsuka, K. Nomoto, and H. Umeda, *Astrophys. J.* **691**, 621 (2009).
- [4] A. Dohi, H. Liu, T. Noda, and M.-A. Hashimoto, *Int. J. Mod. Phys. E* **31**, 2250006 (2022) [[arXiv:2112.13302\[astro-ph.HE\]](#)] [[Search inSPIRE](#)].
- [5] S. Tsuruta and K. Nomoto, Thermal evolution of neutron stars, in *Handbook of Nuclear Physics*, eds. I. Tanihata, H. Toki, and T. Kajino (Springer Nature Singapore, Singapore, 2023), p. 3643.
- [6] P. B. Demorest, T. Pennucci, S. M. Ransom, M. S. E. Roberts, and J. W. T. Hessels, *Nature* **467**, 1081 (2010) [[arXiv:1010.5788\[astro-ph.HE\]](#)] [[Search inSPIRE](#)].
- [7] S. Tsuruta, *Comments Astrophys.* **11**, 151 (1986).
- [8] S. Tsuruta, *Phys. Rep.* **292**, 1 (1998).
- [9] T. Takatsuka, S. Nishizaki, and R. Tamagaki, Universal three-body repulsion suggested by neutron stars, in *New Facet of Three Nucleon Force—50 Years of Fujita Miyazawa*, eds. H. Sakai, K. Sekiguchi, and B. F. Gibson, *American Institute of Physics Conference Series*, vol. **1011** (AIP, College Park, MD, 2008), p. 209.
- [10] S. Tsuruta, Neutron star cooling: II, in *Neutron Stars and Pulsars*, ed. Becker W., *Astrophysics and Space Science Library*, vol. **357** (Springer, Berlin, Heidelberg, 2009), p. 289.
- [11] E. E. Salpeter, *Astrophys. J.* **134**, 669 (1961).
- [12] A. Dohi, K. Nakazato, M.-a. Hashimoto, Y. Matsuo, and T. Noda, *Prog. Theor. Exp. Phys.* **2019**, 113E01 (2019) [[arXiv:1910.01431\[astro-ph.HE\]](#)] [[Search inSPIRE](#)].
- [13] A. Y. Potekhin, G. Chabrier, and D. G. Yakovlev, *Astron. Astrophys.* **323**, 415 (1997) [[arXiv:astro-ph/9706148](#)] [[Search inSPIRE](#)].
- [14] P. Chang and L. Bildsten, *Astrophys. J.* **605**, 830 (2004) [[arXiv:astro-ph/0312589](#)] [[Search inSPIRE](#)].
- [15] G. G. Pavlov, V. E. Zavlin, and D. Sanwal, Thermal radiation from neutron stars: Chandra results, in *Neutron Stars, Pulsars, and Supernova Remnants*, eds. W. Becker, H. Lesch, and J. Trümper (Max-Planck-Institut für extraterrestrische Physik, Garching bei München, 2002), p. 273 [[arXiv:astro-ph/0206024](#)] [[Search inSPIRE](#)].
- [16] R. Kothes, *Astron. Astrophys.* **560**, A18 (2013) [[arXiv:1307.8384\[astro-ph.GA\]](#)] [[Search inSPIRE](#)].
- [17] R. A. Fesen, B. E. Schaefer, and D. Patchick, *Astrophys. J. Lett.* **945**, L4 (2023) [[arXiv:2301.04809\[astro-ph.HE\]](#)] [[Search inSPIRE](#)].
- [18] A. Marino, C. Dehman, K. Kovlakas, N. Rea, J. A. Pons, and D. Viganò, *Nature Astron.* **8**, 1020 (2024) [[arXiv:2404.05371\[astro-ph.HE\]](#)] [[Search inSPIRE](#)].
- [19] B. Posselt and G. G. Pavlov, *Astrophys. J.* **932**, 83 (2022) [[arXiv:2205.06552\[astro-ph.HE\]](#)] [[Search inSPIRE](#)].
- [20] C. Hu, B. Begiçarslan, T. Güver, T. Enoto, G. Younes, T. Sakamoto, P. S. Ray, T. E. Strohmayer, S. Guillot, Z. Arzoumanian et al. *Astrophys. J.* **902**, 1 (2020) [[arXiv:2009.00231\[astro-ph.HE\]](#)] [[Search inSPIRE](#)].
- [21] D. Klochkov, V. Suleimanov, G. Püehlhofer, K. Werner, and A. Santangelo, Constraining parameters of the neutron star in the supernova remnant HESS J1731-347, in *The X-ray Universe 2014*, ed. J.-U. Ness (European Space Agency, Noordwijk, 2014), p. 100.

- [22] V. E. Zavlin, J. Trümper, and G. G. Pavlov, *Astrophys. J.* **525**, 959 (1999).
 [23] E. V. Gotthelf, J. P. Halpern, and F. D. Seward, *Astrophys. J.* **627**, 390 (2005) [[arXiv:astro-ph/0503424](#)] [[Search inSPIRE](#)].
 [24] P. M. Woods, V. E. Zavlin, and G. G. Pavlov, *Astrophys. Space Sci.* **308**, 239 (2007) [[arXiv:astro-ph/0608483](#)] [[Search inSPIRE](#)].
 [25] D. Page, J. M. Lattimer, M. Prakash, and A. W. Steiner, *Astrophys. J. Suppl.* **155**, 623 (2004) [[arXiv:astro-ph/0403657](#)] [[Search inSPIRE](#)].
 [26] A. M. Pires, C. Motch, R. Turolla, S. B. Popov, A. D. Schwope, and A. Treves, *Astron. Astrophys.* **583**, A117 (2015) [[arXiv:1508.05246\[astro-ph.HE\]](#)] [[Search inSPIRE](#)].

Table A1. Observation data. $t(\text{age})$ is in year, L_γ^∞ is luminosity in units of ergs s^{-1} . Ages without errors are based on historic age or characteristic age. Columns 2 and 3 are the data used in this 2026 paper, whereas columns 5 and 6 are the data used in Ref. [3]

Source	$\log_{10} t$ years 2026 data	$\log_{10} L_\gamma^\infty$ ergs s^{-1}	Reference	$\log_{10} t$ years 2009 data	$\log_{10} L_\gamma^\infty$ ergs s^{-1}
Cas A	2.51	$33.86^{+0.11}_{-0.11}$	[19]	2.51	<34.50
J1818	$3.53^{+0.25}_{-0.10}$	$33.92^{+0.26}_{-0.30}$	[20]	–	–
J1732	$3.54^{+0.24}_{-0.24}$	$34.08^{+0.13}_{-0.14}$	[21]	–	–
Puppis A	$3.55^{+0.05}_{-0.05}$	$33.60^{+0.10}_{-0.10}$	[22]	$3.72^{+0.18}_{-0.19}$	$33.90^{+0.07}_{-0.08}$
Kes 79	$3.80^{+0.10}_{-0.10}$	$33.60^{+0.10}_{-0.10}$	[23]	–	–
1E 1207	$3.85^{+0.45}_{-0.45}$	$33.50^{+0.50}_{-0.50}$	[24]	3.85	$33.50^{+0.07}_{-0.08}$
RX J0002	$3.96^{+0.08}_{-0.08}$	$33.21^{+0.12}_{-0.13}$	[25]	$3.96^{+0.08}_{-0.08}$	$33.21^{+0.12}_{-0.13}$
J1046 ¹	$4.26^{+0.22}_{-0.22}$	<32.34	[26]	4.31	<32.70
J1412	5.45	$33.57^{+0.38}_{-0.39}$	[27]	–	–
Crab	2.90	<34.38	[28]	2.90	<34.38
PSR J1509	–	–	–	3.19	<33.90
3C58 ¹	$3.79^{+0.12}_{-0.25}$	$32.15^{+0.24}_{-0.24}$	[18]	2.91	<33.00
PSR J1124	$3.45^{+0.15}_{-0.15}$	<33.30	[29]	$3.45^{+0.15}_{-0.15}$	<33.30
J0852 ^{1,2}	$3.57^{+0.13}_{-0.19}$	$32.30^{+0.11}_{-0.15}$	[18]	–	–
PSR J0007 ¹	$4.10^{+0.10}_{-0.10}$	<32.30	[29]	$4.10^{+0.10}_{-0.10}$	<32.30
PSR B1706 ¹	4.20	$31.90^{+0.20}_{-0.20}$	[30]	4.24	$32.37^{+0.56}_{-0.56}$
PSR J2021	4.24	$32.70^{+0.16}_{-0.16}$	[31]	–	–
PSR B1046	4.31	<32.70	[32]	4.31	<32.70
PSR B1823	4.33	<33.90	[32]	4.33	<33.90
PSR B0833 (Vela)	$4.43^{+0.10}_{-0.10}$	$32.20^{+0.10}_{-0.10}$	[33]	4.05	$32.58^{+0.12}_{-0.17}$
J0617	$4.54^{+0.06}_{-0.08}$	$32.41^{+0.02}_{-0.01}$	[34]	–	–
PSR J0538	$4.70^{+0.10}_{-0.10}$	$32.80^{+0.10}_{-0.10}$	[35]	4.47	$32.83^{+0.50}_{-0.51}$
PSR B2334 ¹	$4.70^{+0.10}_{-0.10}$	$31.78^{+0.26}_{-0.40}$	[18]	4.61	<33.40
PSR B1727	$4.78^{+0.08}_{-0.10}$	<31.53	[36]	–	–
PSR B0656	$5.00^{+0.10}_{-0.10}$	$32.75^{+0.05}_{-0.05}$	[15]	5.04	$32.74^{+0.10}_{-0.10}$
PSR B1951	5.03	<33.90	[32]	5.03	<33.90
PSR J1740	5.06	$32.15^{+0.05}_{-0.05}$	[37]	–	–
PSR J0154	–	–	–	5.29	<32.14
PSR B1822	5.37	$31.41^{+0.17}_{-0.18}$	[38]	–	–
PSR J0633	5.53	$32.05^{+0.45}_{-0.45}$	[39]	5.53	$31.86^{+0.51}_{-0.52}$
PSR J1741	5.59	$32.49^{+0.16}_{-0.17}$	[40]	–	–
PSR B1055	5.75	$32.60^{+0.17}_{-0.25}$	[15]	5.73	$32.60^{+0.17}_{-0.25}$
PSR J1957	5.92	$30.93^{+0.22}_{-0.23}$	[41]	–	–
PSR B2224	6.05	<31.40	[42]	6.05	<31.40

Table A1. Continued

Source	$\log_{10} t$ years 2026 data	$\log_{10} L_{\gamma}^{\infty}$ ergs s $^{-1}$	Reference	$\log_{10} t$ years 2009 data	$\log_{10} L_{\gamma}^{\infty}$ ergs s $^{-1}$
PSR J2043	6.08	<31.25	[43]	6.08	<31.25
PSR J0357	6.11 $^{+0.40}_{-0.41}$	31.18 $^{+0.42}_{-0.58}$	[31]	–	–
PSR J1836	6.26	30.15 $^{+0.33}_{-0.26}$	[44]	–	–
PSR B0628	6.44	<30.94	[45]	6.44	<30.94
PSR B1929	6.49	<30.70	[32]	6.49	<30.70
PSR B0823	6.69	<31.00	[32]	6.69	<31.00

¹These sources are sometimes referred to as “Vela-like.” ²This source is sometimes referred to as “Vela Jr.”

- [27] S. Mereghetti, M. Rigoselli, R. Taverna, L. Baldeschi, S. Crestan, R. Turolla, and S. Zane, *Astrophys. J.* **922**, 253 (2021) [[arXiv:2110.14930\[astro-ph.HE\]](#)] [[Search inSPIRE](#)].
- [28] M. C. Weisskopf, S. L. O’Dell, F. Paerels, R. F. Elsner, W. Becker, A. F. Tennant, and D. A. Swartz, *Astrophys. J.* **601**, 1050 (2004) [[arXiv:astro-ph/0310332](#)] [[Search inSPIRE](#)].
- [29] J. P. Hughes, P. O. Slane, S. Park, P. W. A. Roming, and D. N. Burrows, *Astrophys. J. Lett.* **591**, L139 (2003) [[arXiv:astro-ph/0305383](#)] [[Search inSPIRE](#)].
- [30] K. E. McGowan, S. Zane, M. Cropper, J. A. Kennea, F. A. Córdova, C. Ho, T. Sasseen, and W. T. Vestrand, *Astrophys. J.* **600**, 343 (2004) [[arXiv:astro-ph/0309445](#)] [[Search inSPIRE](#)].
- [31] A. Kirichenko, A. Danilenko, P. Shternin, Y. Shibano, E. Ryspaeva, D. Zyuzin, M. Durant, O. Kargaltsev, G. Pavlov, and A. Cabrera-Lavers, *Astrophys. J.* **802**, 17 (2015) [[arXiv:1501.04594\[astro-ph.SR\]](#)] [[Search inSPIRE](#)].
- [32] W. Becker and G. G. Pavlov, (2002), [[arXiv:astro-ph/0208356](#)] [[Search inSPIRE](#)].
- [33] G. G. Pavlov, V. E. Zavlin, D. Sanwal, V. Burwitz, and G. P. Garmire, *Astrophys. J. Lett.* **552**, L129 (2001) [[arXiv:astro-ph/0103171](#)] [[Search inSPIRE](#)].
- [34] D. A. Swartz, G. G. Pavlov, T. Clarke, G. Castelletti, V. E. Zavlin, N. Bucciantini, M. Karovska, A. J. van der Horst, M. Yukita, and M. C. Weisskopf, *Astrophys. J.* **808**, 84 (2015) [[arXiv:1506.05507\[astro-ph.HE\]](#)] [[Search inSPIRE](#)].
- [35] V. E. Zavlin and G. G. Pavlov, *Mem. Soc. Astron. Ital.* **75**, 458 (2004) [[arXiv:astro-ph/0312326](#)] [[Search inSPIRE](#)].
- [36] P. Shternin, A. Kirichenko, D. Zyuzin, M. Yu, A. Danilenko, M. Voronkov, and Y. Shibano, *Astrophys. J.* **877**, 78 (2019) [[arXiv:1904.06368\[astro-ph.HE\]](#)] [[Search inSPIRE](#)].
- [37] S. Bogdanov, M. van den Berg, C. O. Heinke, H. N. Cohn, P. M. Lugger, and J. E. Grindlay, *Astrophys. J.* **709**, 241 (2010) [[arXiv:0911.3146\[astro-ph.HE\]](#)] [[Search inSPIRE](#)].
- [38] W. Hermsen, L. Kuiper, J. W. T. Hessels, D. Mitra, J. M. Rankin, B. W. Stappers, G. A. E. Wright, R. Basu, A. Szary, and J. van Leeuwen, *Mon. Not. R. Astron. Soc.* **466**, 1688 (2017) [[arXiv:1612.04392\[astro-ph.HE\]](#)] [[Search inSPIRE](#)].
- [39] O. Y. Kargaltsev, G. G. Pavlov, V. E. Zavlin, and R. W. Romani, *Astrophys. J.* **625**, 307 (2005) [[arXiv:astro-ph/0502076](#)] [[Search inSPIRE](#)].
- [40] A. Karpova, A. Danilenko, Y. Shibano, P. Shternin, and D. Zyuzin, *Astrophys. J.* **789**, 97 (2014) [[arXiv:1405.5041\[astro-ph.SR\]](#)] [[Search inSPIRE](#)].
- [41] D. A. Zyuzin, A. V. Karpova, Y. A. Shibano, A. Y. Potekhin, and V. F. Suleimanov, *Mon. Not. R. Astron. Soc.* **501**, 4998 (2021) [[arXiv:2101.09989\[astro-ph.HE\]](#)] [[Search inSPIRE](#)].
- [42] C. Y. Hui and W. Becker, *Astron. Astrophys.* **486**, 485 (2008) [[arXiv:0707.0800\[astro-ph\]](#)] [[Search inSPIRE](#)].
- [43] W. Becker, M. C. Weisskopf, A. F. Tennant, A. Jessner, J. Dyks, A. K. Harding, and S. N. Zhang, *Astrophys. J.* **615**, 908 (2004) [[arXiv:astro-ph/0405180](#)] [[Search inSPIRE](#)].
- [44] P. Arumugasamy, Rotation powered pulsars in the X-rays, PhD thesis (Pennsylvania State University, University Park, PA, 2015).
- [45] E. Tepedelenlioğlu and H. Ögelman, *Astrophys. J. Lett.* **630**, L57 (2005) [[arXiv:astro-ph/0505461](#)] [[Search inSPIRE](#)].

