Astronomische Nachrichten

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A Brief, Biased View of Neutron Star Cooling

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Received: 30 October 2024 | **Accepted:** 31 October 2024

Funding: This work was supported by Natural Sciences and Engineering Research Council of Canada, RGPIN-2023-04264.

Keywords: dense matter | neutrinos | stars: neutron | x-rays: binaries

ABSTRACT

This is a concise and non-technical review of topics related to neutron star (NS) cooling, for both young NSs and NSs in low-mass x-ray binaries. Neutrino emission from the NS core drives cooling rates, via different processes including Urca processes and pair breaking and formation at the neutron superfluid critical temperature. Key insights have been given by the temperatures of the coldest NSs, by the rapid (questioned) cooling of the Cas A NS, and by measuring the cooling of transient NS x-ray binaries after accretion episodes.

1 | Introduction

Neutron stars (NSs) contain extremely dense material, that cannot be studied in such a dense and stable state elsewhere in the Universe. This material, which may be composed primarily of neutrons, is theorized to exhibit intriguing properties, which may include superfluidity and rearrangement of its constituent quarks into other hadronic particles (or possibly even into a free quark state). One of the most powerful tools to study the physics of NS interiors is the temperature of NSs. By studying how NSs are heated and cooled, we get a view of the thermal state of the interior of the star.

In this article, I will give a simple review of some interesting current problems related to NS cooling. I first briefly remind readers of NS structure (Section 2), and then simply summarize key cooling mechanisms of NSs (Section 3). Section 4 describes some recent results on the cooling of young NSs, with a focus on the young NS in Cas A. Section 5 describes interesting constraints on NS crusts from observations of x-ray binaries just after accretion episodes, and Section 6 discusses results on NS cores from the coldest NSs in x-ray binaries between outbursts. Section 7 concludes. I will not cover the cooling of NSs with high magnetic fields (magnetars), and heating due to decaying magnetic fields, as that introduces additional complex theory in which I am not an expert; some papers covering magnetar heating and cooling include Beloborodov and Li (2016), Coti Zelati et al. (2018), Pons et al. (2007), Turolla, Zane, and Watts (2015), and Viganò et al. (2013).

2 | Structure of NSs

NSs span a wide range of density and thus physics (see Figure 1). Many NSs possess atmospheres, gaseous (often ionized) material with a scale height of a few centimeters. The composition of this atmosphere alters the observed spectrum, which can in some cases be distinguished by x-ray spectroscopy (Ho and Heinke 2009; Potekhin 2014; Rajagopal and Romani 1996; Zavlin, Pavlov, and Shibanov 1996). Below the atmosphere is a liquid envelope of normal (high-density) matter, 10s of meters deep; this may be dominated by light elements (e.g., H, He, O) or heavier elements (e.g., Fe), affecting the insulating properties of the envelope.

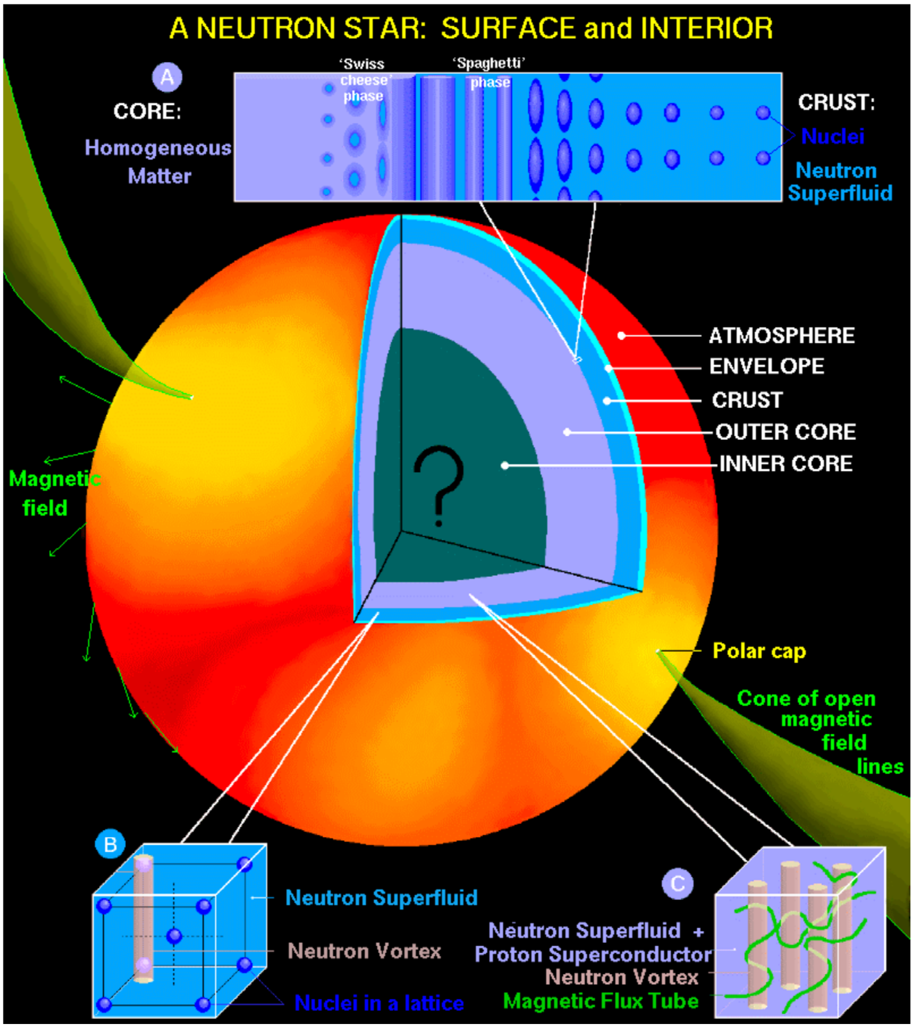

FIGURE 1 | Illustration of the structure of a NS, by Dany Page.

Below the envelope is the crust of the NS, a (quasi-) solid layer where the material transitions from an ionic lattice to NS interior matter. This transition probably includes a so-called "pasta" phase, where the nucleons bind into various complex shapes in configurations larger than nuclei.

The outer core of the NS is thought to consist largely of neutrons, with small admixtures of protons, electrons, and muons. As the density increases toward the inner core, some or all of the quarks may rearrange into other forms, such as hyperons or kaons; or conceivably become unbound from baryons into a free quark soup.

3 | Cooling Physics

3.1 | Cooling of Young Neutron Stars

NSs are born at extremely high temperatures of billions of degrees, in the hearts of supernovae. For the first 10^5-10^6 years, their cooling is thought to be dominated by neutrino emission processes from their cores, after which surface photon emission dominates (see Figure 2). It takes roughly a hundred years for the cooling wave (from neutrino emission in the core) to reach the surface; this explains the initial plateau and then sharp drop of the surface temperature after a century. See Yakovlev and Pethick (2004), Page et al. (2004), and Potekhin, Pons, and Page (2015) for detailed reviews of NS cooling.

The most efficient neutrino cooling mechanism in NS cores is the standard (proton) "direct Urca" process, in which baryons transform between being a proton or neutron, emitting or absorbing a lepton (ℓ, either an electron or muon);

$$n \rightarrow p^+ + \ell^- + \overline{\nu}_\ell$$

$$p^+ + \ell^- \rightarrow n + \nu_\ell$$

These reactions can produce substantial neutrino emission, rapidly cooling the star, if the chemical potential is energetically favorable to protons (roughly >10% protons); this may be true only above some critical density. If other particles (e.g., hyperons, pions, kaons) are present in significant numbers, then very efficient Urca cooling processes involving these particles may occur. If direct (proton) Urca is permitted without impediment, NSs can cool very rapidly, to near-undetectability within 100 years (see Figure 3). If direct Urca is permitted above a density threshold, then higher-mass NSs may access it, while lower-mass NSs will not.

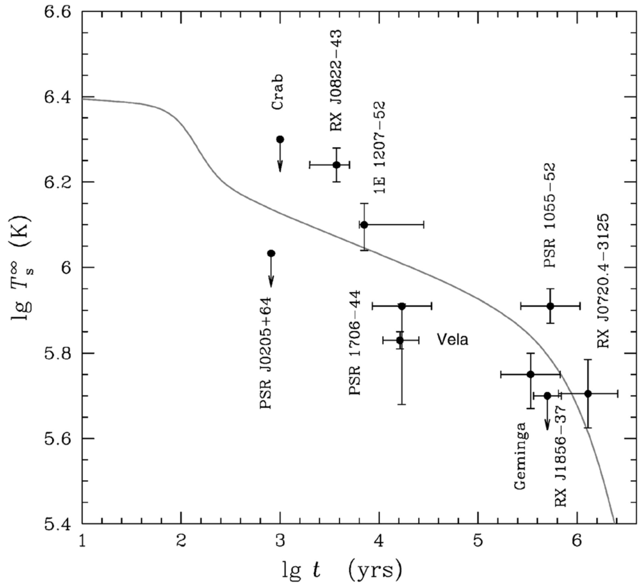

FIGURE 2 | An example cooling curve for a young NS, from Yakovlev and Pethick (2004), with some datapoints from young NS temperatures.

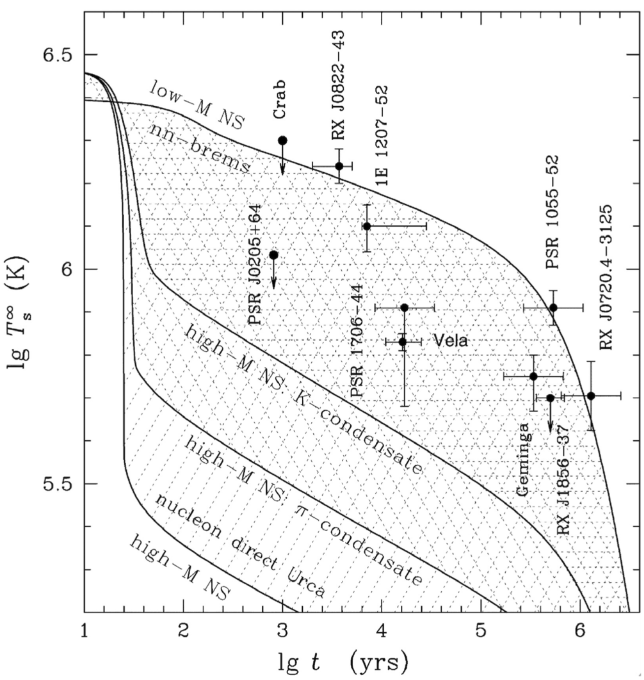

FIGURE 3 | Direct Urca cooling models, shown for high-mass stars that access direct Urca (for nucleons, kaons, or muons) as well as for lower-mass stars cooling by neutron bremsstrahlung. Some datapoints from young NS temperatures are plotted. From Yakovlev and Pethick (2004).

If direct Urca reactions are not permitted, NSs will cool by slower methods; modified Urca cooling, which is like direct Urca but requires participation of another nucleon; and/or nucleon-nucleon bremsstrahlung. These slower processes are termed minimal cooling. A significant range in photon cooling rates can be achieved by variation in the composition of the envelope, as light elements are a more efficient conductor; thus a NS with a light-element envelope will be hotter earlier and cool more quickly (Figure 4; e.g., Page et al. 2004).

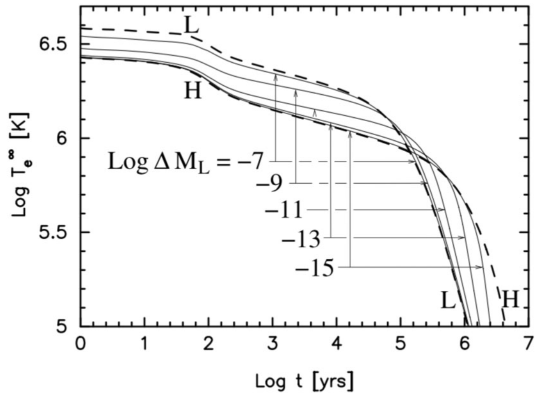

FIGURE 4 | Effects of different amounts of light elements (indicated by the log of the mass of light elements, in $M_\odot$) in the NS envelope, from Page et al. (2004).

3.2 | Effects of Superfluidity

As NSs cool, an energy gap appears between unpaired and paired states, in which like nucleons are attracted and "pair up" into so-called Cooper pairs, producing a superfluid state. Neutrons and protons are thought to settle into different density-dependent superfluid states (with a different critical temperature for each superfluid state) in the cores and crusts of NSs, producing several effects, including spin-up episodes known as "glitches" (Anderson and Itoh 1975), and several effects on the cooling of NSs (Page et al. 2014). First, the pairing of either neutrons or protons suppresses all Urca processes, direct and modified, preventing rapid cooling where nucleons are fully paired. Second, the pairing of nucleons alters the heat capacity of the relevant nucleon (neutrons), reducing their heat capacity at low temperatures, thus at late times. Finally, around the critical temperature, nucleons enter into paired states, occasionally emitting neutrino-antineutrino pairs; then gain enough thermal energy to break the pairing, and then fall into paired states again. This "pair breaking and formation" (PBF) process has the effect of rapidly cooling the NS over a short period (Flowers, Ruderman, and Sutherland 1976). These effects are illustrated in Figure 5, from Page et al. (2004), which show that (a) pairing suppresses cooling during the early neutrino cooling era; (b) the reduction of heat capacity means that paired stars cool faster in the late photon cooling era; (c) PBF produces faster early cooling.

4 | Young Neutron Stars

The surface temperatures or luminosities of young NSs can be measured in the x-ray (or sometimes UV), and their ages can be estimated via associations with supernova remnants or groups of young stars, or for pulsars by using characteristic ages (how long it would take for them to reach their current spin periods, from an initial miniscule period, at their current spindown rate; clearly this is a very rough estimate). This allows us to plot the positions of young NSs, and compare them with cooling models. A compilation (Figure 6) of young NS ages and temperatures by Potekhin et al. (2020) demonstrates that the majority of young NSs could be explained by "minimal cooling" scenarios (those using only modified Urca and pairing, without direct Urca). However, a few

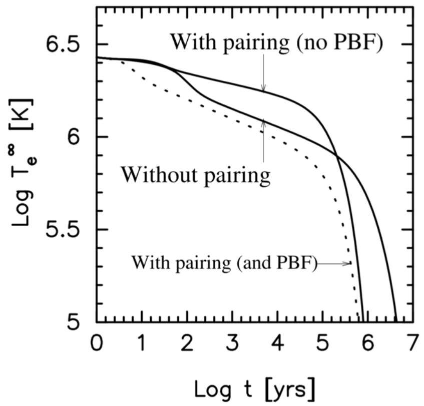

FIGURE 5 | Simple illustration of superfluid effects on NS cooling, from Page et al. (2004). Lines indicate cooling trajectories of NSs where pairing suppresses Urca processes, without including PBF; NSs without pairing; and NSs including the effects of both pairing and PBF.

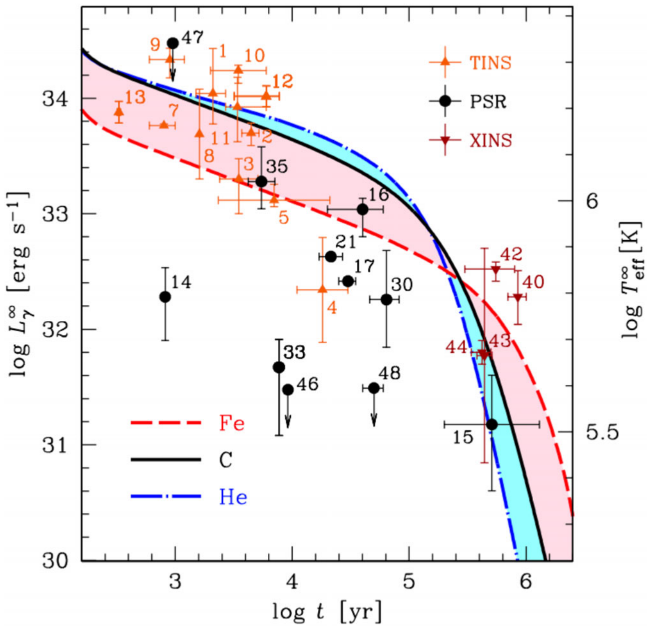

FIGURE 6 | Compilation by Potekhin et al. (2020) of young NS ages and temperatures, including "TINS" thermally emitting isolated NSs; "PSR" pulsars; and "XINS" nearby NSs detected in the x-ray. The curves represent theoretical cooling curves with heat blanketing envelopes composed of Fe, C, or He (cf. Figure 4).

objects appear to be much colder than these tracks can explain, requiring fast cooling processes such as direct Urca to operate in some NSs (e.g., Halpern et al. 2004; Kaplan et al. 2004; Slane, Helfand, and Murray 2002).

The youngest NS known in our galaxy is the Cassiopeia A NS (Cas A), only ~300 years old. Heinke and Ho (2010) argued that *Chandra* datasets over 10 years showed a decrease of 4% in the surface temperature of the Cas A NS (Figure 7). This was considered such a sharp decline that neutrons in the Cas A NS are likely in the midst of their PBF transition to a superfluid state (Page et al. 2011; Shternin et al. 2011). The relatively high temperature suggests that the protons became superfluid even earlier, suppressing modified (or direct) Urca cooling. Alternative

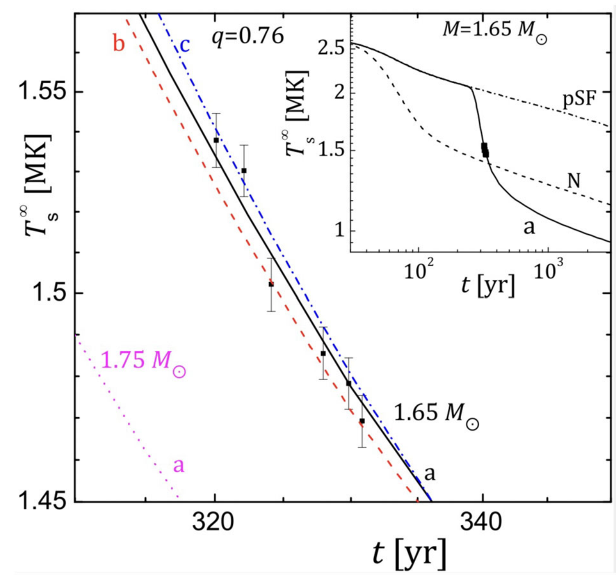

FIGURE 7 | Initial Cas A temperature measurements using *Chandra* ACIS data, showing a 4% temperature decline per decade. Inset shows the superfluid model, with the modeled temperature cooling slowly initially (due to the proton superfluid suppressing modified Urca cooling), and then rapidly dropping due to superfluid PBF as the core temperature passes the neutron superfluid critical temperature (plot from Shternin et al. 2011).

explanations for this rapid cooling have also been advanced (e.g., Blaschke et al. 2012; Hamaguchi et al. 2018).

However, the *Chandra* ACIS data favoring rapid cooling suffers from potential systematic issues; the NS spectrum is piled up (multiple photons may be registered as one photon, or misinterpreted as a cosmic ray and discarded), while the ACIS detector suffers increasing levels of contamination. Interactions between these effects could alter the observed cooling rate. Elshamouty et al. (2013) analyzed several *Chandra* observations of the Cas A NS with a different detector, HRC-S, finding a temperature drop of only $1.0 \pm 0.7\%$ over a decade. Posselt et al. (2013) analyzed two ACIS observations taken in a different mode, reading out only part of the detector to prevent pileup, and did not find a significant temperature drop between 2006 and 2012. Adding two more ACIS subarray observations produced a best-fit temperature decline of 1.5%–2.3% per decade (Posselt and Pavlov 2022). Intriguingly, recalibration and extension of the original full-frame ACIS data indicates a consistent temperature decline of 1.6%–2.2% per decade (Shternin et al. 2023). Finally, Zhao, Heinke et al. in prep.) are analyzing new HRC-S observations of Cas A, with preliminary results of a temperature decline of $0.9 \pm 0.2\%$ per decade. Thus, three separate lines of experiment are converging (or nearly) to say that the Cas A NS is indeed cooling, but at ~1/4 of the originally claimed rate. Such a lower cooling rate would be easier for the superfluid PBF transition explanation to accomodate, while still far too fast for standard (modified Urca) cooling to explain.

5 | X-Ray Binary Cooling Crusts

NSs can also be heated by accretion, in low-mass x-ray binary systems, some of which undergo transient accretion "outbursts" followed by longer periods of quiescence. Accretion releases heat at the surface, but also deep inside the crust, as pressure forces nuclear fusion ("deep crustal heating"; Haensel and Zdunik 1990). Observing thermal emission from NSs after outbursts allows us to measure heat trickling from different layers of the NS crust, and thus to infer how deep the heat is produced, how much heat is produced, and the insulating properties of the crustal layers (Rutledge et al. 2002). Observations of multiple transients with XMM-Newton and *Chandra* over timescales of weeks to decades have revealed strong crustal cooling, with differences in the cooling rate and amplitude (see Figure 8; Wijnands, Degenaar, and Page 2017).

The low-mass x-ray binaries KS 1731-260 and MXB 1659-29 returned to quiescence in 2001 after outbursts of 12 and 2.5 years duration (respectively), and x-ray observations have measured the cooling of their crusts since then (e.g., Cackett et al. 2008; Merritt et al. 2016). The relatively rapid cooling implies that the crust has high thermal conductivity, with a crystalline (rather than amorphous) structure, and contains a neutron superfluid, reducing the neutron heat capacity in the crust (Brown and Cumming 2009; Shternin et al. 2007). Figure 9 shows how the speed of cooling constrains the impurity parameter Q.

However, MXB 1659-29 also showed evidence for continuing cooling 11 years after its outburst ended (Cackett et al. 2013, not shown in Figure 8), which would imply a low thermal conductivity layer in the deep crust with non-superfluid neutrons, likely in a "pasta" layer (Deibel et al. 2017), or else as a crustal

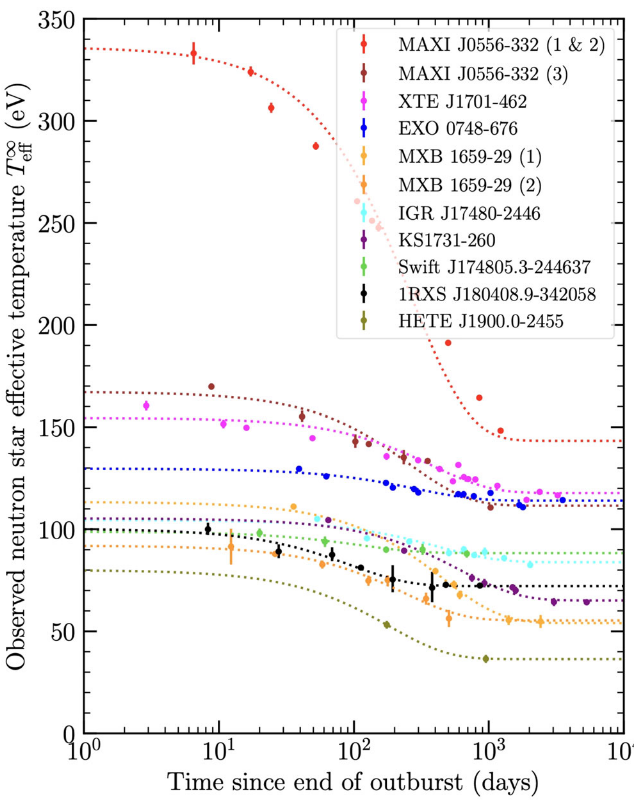

FIGURE 8 | Crust cooling curves of 11 transient x-ray binaries after outbursts, showing a variety of cooling amplitudes and timescales. Plot courtesy of D. Page, modified from Page et al. (2022).

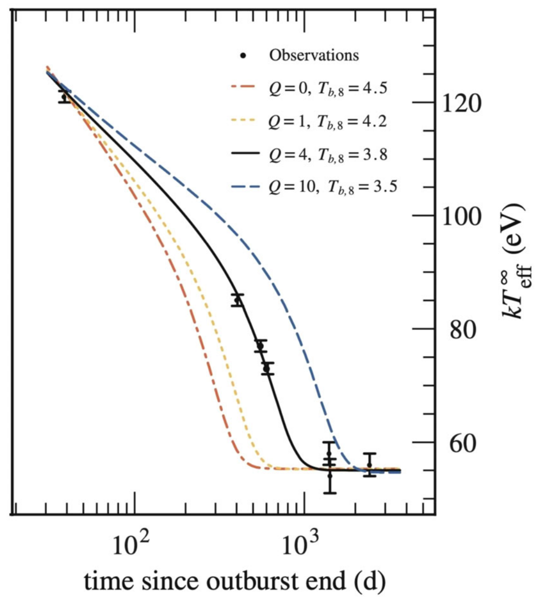

FIGURE 9 | Crust cooling curve of MXB 1659-29 (NS temperature vs. days after accretion ended), with model cooling curves for different choices of impurity parameter Q (other parameters adjusted to fit the first point), from Brown and Cumming (2009).

neutron superfluid that does not have an energy gap (Allard and Chamel 2024). However, the small number of counts in the crucial 11-year observation of MXB 1659-29 could also be explained by increased photoelectric absorption of the x-rays by matter in the accretion disk, plausible given the edge-on state of the system (Cackett et al. 2013), and KS 1731-260 did not show such continued cooling at 15 years into quiescence (Merritt et al. 2016). Unfortunately for resolving this conundrum, MXB 1659-29 returned to outburst in 2015 (Sharma et al. 2018); following its quiescent cooling until ~2028, along with other cooling NSs (e.g., Ootes et al. 2019), would be very helpful.

Deep crustal heating was thought to provide 1.5–2 MeV per accreted nucleon of heating (Haensel and Zdunik 2008). However, observations of crustal cooling have shown evidence for significant extra heating at shallow crustal depths (e.g., Brown and Cumming 2009; Degenaar, Brown, and Wijnands 2011; Degenaar et al. 2019; Merritt et al. 2016; Turlione, Aguilera, and Pons 2015). Typically this excess heating has been measured at another 1–2 MeV/nucleon. However, the bright distant transient MAXI J0556-332 showed larger extra heating, 15–17 MeV/nucleon after its first outburst (Deibel et al. 2015; Homan et al. 2014; see Figure 8). Some NSs have shown similar shallow heating in multiple outbursts (MXB 1659-29, Parikh et al. 2019) while different outbursts produce very different amounts of shallow heating in others (Aql X-1, Degenaar et al. 2019; MAXI J0556-332, Parikh et al. 2017). The origin of this shallow heating is not understood, with suggestions ranging from chemical convection (Medin and Cumming 2015), to mechanical energy in the ocean layer (Inogamov and Sunyaev 2010), to a "hyperburst" burning oxygen and neon in deep layers (Page et al. 2022).

The original deep crustal heating paradigm assumed that accreted elements were compressed by later accretion, with changes in composition caused by pressure-induced reactions (Haensel and Zdunik 1990). However, Gusakov and Chugunov (2020) recently pointed out that neutrons are free to move within the crust, and thus will move so as to equilibrate the free neutron chemical potential, making accreted NS crusts energetically similar to ground-state NS crusts (as assumed for the original post-supernova crust). This reduces the heat released in the deep crust during accretion, but given the free parameters remaining in shallow heating it is also possible to fit crust cooling curves with this new model (Potekhin, Gusakov, and Chugunov 2023).

6 | Cold Cores of X-Ray Binaries

A portion of the heat that is produced in the deep crust during accretion episodes will flow into the core of the NS and back out during long quiescent periods, coming to equilibrium on timescales of $\sim 10^4$ years (Brown, Bildsten, and Rutledge 1998). Thus, the temperature of NSs in deep quiescence, after their crusts have cooled back to equilibrium with their cores, should reflect their long-term average mass transfer rate. However, heat can also leave the core via neutrino emission mechanisms discussed in Section 3, producing unusually cold NSs. Indeed, many NSs have been observed to be substantially cooler than predicted by “standard” NS cooling (Campana et al. 2002; Colpi et al. 2001; Heinke et al. 2009, 2007; Jonker et al. 2007; Wijnands et al. 2001). This indicates that strongly enhanced neutrino cooling must be necessary, at the level provided by direct Urca processes, in the most massive NSs in x-ray binaries (Beznogov and Yakovlev 2015; Wijnands, Degenaar, and Page 2013; Yakovlev et al. 2004; see Figure 10). Study of the cooling of MXB 1659-29 after outbursts allow strong constraints on its neutrino luminosity, which appear to require direct Urca emission (Brown et al. 2018). Intriguingly, permitting direct Urca in NS cores requires small energy gaps in the core neutron superfluid (Fortin et al. 2018; Han and Steiner 2017), which appears to be in tension with the superfluid properties necessary to explain the Cas A NS cooling.

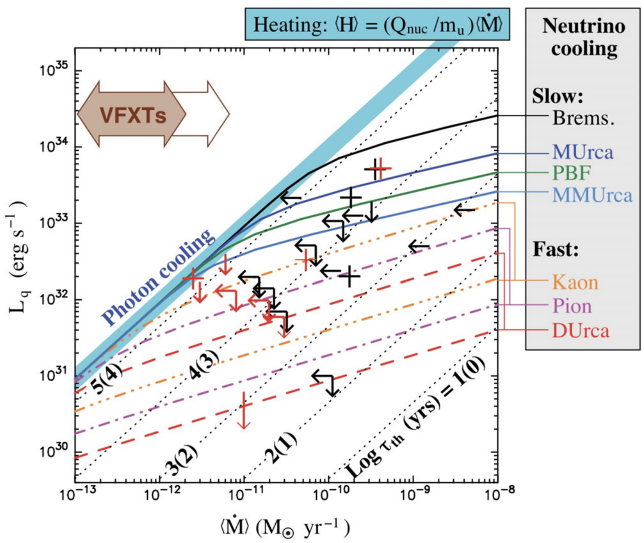

FIGURE 10 | Inferred long-term mass transfer rate of many different x-ray binaries, compared to their quiescent thermal x-ray luminosity, and to predictions of several neutrino cooling mechanisms that may be operational in NS cores (plot from Wijnands, Degenaar, and Page 2013).

Alternatively, the coldest NSs may have very different long-term (10^4 years) mass transfer rates than observed (over $\sim$50 years). SAX J1808.4-3658's extremely cold state is difficult to understand, as the current mass constraints, while poor, suggest a relatively low-mass ($1.0^{+0.3}_{-0.2}\,M_\odot$) NS (Wang et al. 2013), while its fast cooling suggests it should have a mass well above average. This conflict might be rectified if SAX J1808.4-3658 is in a temporary x-ray binary phase, and spent most of the last 10^4 years in a pulsar state. Its initially fast orbital expansion suggested it might indeed detach soon (di Salvo et al. 2008), but its orbit has reversed and is now shrinking (Illiano et al. 2023); its orbital variation, and longer-term behavior, remains poorly understood.

7 | Conclusions

NS cooling, measured via x-ray observations, significantly constrains the physics of NS cores and crusts. Many young NSs follow a relatively standard cooling track, consistent with cooling by modified Urca and/or pair breaking and formation as the neutrons transition into a superfluid state. However, some are significantly colder, indicating enhanced neutrino cooling processes such as direct Urca must be active in the cores of the most massive NSs. The young NS in the Cas A supernova remnant appears to show detectable cooling, in the range of 1%–2% temperature decrease per year. This rapid cooling has been attributed to pair breaking and formation as neutrons in the interior transition to a superfluid, though other explanations remain possible.

Older NSs in x-ray binaries experiencing transient accretion test the thermal properties of both the crust and core. Their cooling in the weeks to years after an accretion episode reveals the conductivity of the crust and the magnitude of crustal heating. Recent observations have imposed strong limits on crustal impurities, and produced evidence for additional sources of shallow crustal heating during accretion, that vary between accretion episodes. The baseline thermal quiescent emission is set by heat that has collected in the NS core over many outbursts. Observations of several quiescent NSs show evidence for very cold NSs, that appear to require rapid cooling on the scale that can be provided by direct Urca.

The details of NS thermal evolution still have many unanswered questions, such as: Are neutron superfluid gaps large or small? What is the source of shallow heating observed in cooling NS crusts? Which process (direct Urca with protons, or something more exotic) cools the fastest-cooling NSs? What is the mass threshold at which this process is available in NS cores? The results so far have depended on access to highly sensitive x-ray telescopes, such as XMM-Newton and particularly the *Chandra* x-ray Observatory; continued advances will require continued access to these telescopes, and eventually to more powerful successors.

Acknowledgments

I particularly thank Peter Shternin for extensive suggestions, and Dany Page for providing an updated version of Figure 8. I also thank Dima Yakovlev for a great suggestion, and Dany Page, Peter Shternin, Dima Yakovlev, Ed Brown, Sasha Potekhin, and Rudy Wijnands for permissions to reuse figures.

Conflicts of Interest

The author declares no conflicts of interest.

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