Neutron Star Cooling

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Abstract

Neutron Stars are born in hot supernova explosions, retaining their parent star's core mass and spin, but reducing the size of the mass to the size of a small city. With densities nearing the density of atomic nuclei and masses around the mass of our sun, they are some of the most massive and compact objects in the universe. There is much to be gained from understanding Neutron Star (NS) cooling processes including understanding NS x-ray emission and determining the radius of the star. Additionally, understanding Neutron Star development and cooling stages has implications for constraining the nuclear Equation of State (EOS), an unresolved problem in astrophysics with the potential to better understand the nature of fundamental particles under extreme relativistic conditions and high densities. We investigate various cooling processes for an isolated Neutron Star and the comparison between theoretical determinations of Neutron Star cooling and experiments. We relay the most recent research on the subject of Neutron Star Cooling, outlining details of recent advances towards determining a NS radius as well as the significance of understanding Neutron Star cooling for the determination of a Neutron Star equation of state (EOS). We discuss the significance of prior and recent advancements.

Keywords:
Neutron Star, Neutron Star Cooling, Urca Process

1. Introduction

1.1. Background

Neutron Stars are incredibly massive objects, born in the remnants of hot supernova explosions. With masses nearing the density of an atomic nucleus, they retain their parent star's mass and spin, reducing the radius of the mass to the size of a small city. There is much to be gained from understanding Neutron Star cooling from to understanding Neutron Star x-ray emission, determining the radius of the star, and better constraining the Nuclear Equation of State (EOS).

The foundation for developing the first neutron star cooling theory was laid by Tsuruta and Cameron in 1966, who outlined the general structure of the theory and many of the basic concepts [4]. They formulated the basic elements of the theory including the relationship between the internal and surface temperatures of a neutron star and the neutrino and photon cooling stages. As progress was made in the 1980s and 1990s due to the space observatories *Einstein* and *ROSAT*, scientists were able to first reliably detect x-ray thermal radiation from isolated neutron stars, contributing a great amount of progress to the theoretical studies of neutron star evolution. Additionally, superfluidity was recognized as an important regulator of cooling in superfluid cores at this time. More recent data collected by x-ray observatories *Chandra* and *XMM-Newton* gave even more insight into the development of the cooling theory.

Today, the temperature of Neutron Stars is of prime interest. We can compare theoretical cooling curves to observations to determine constraints on the NS equation of state. Understanding the Equation of State of a NS is

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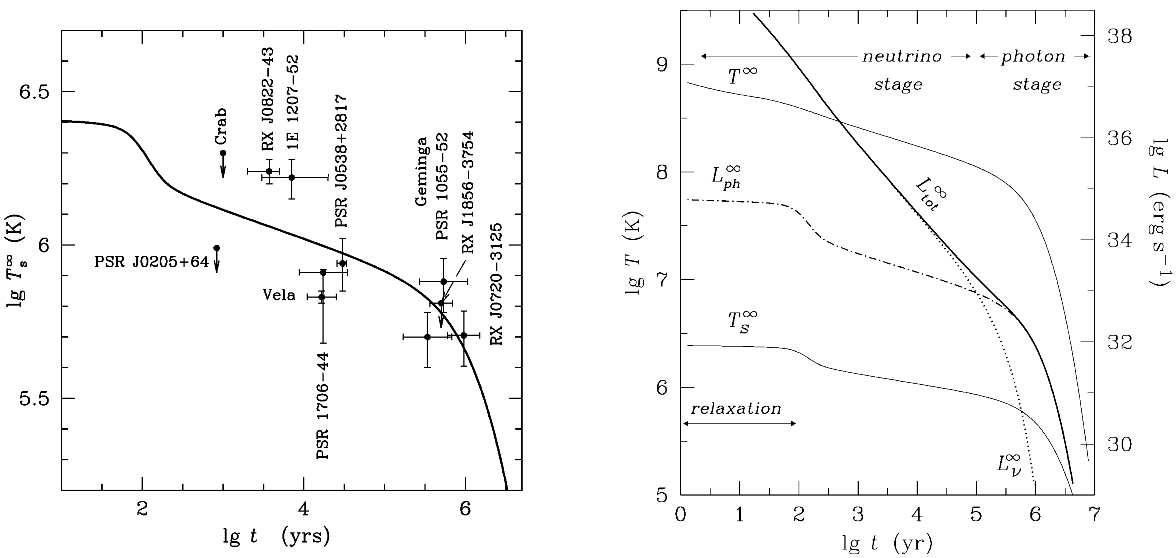

Figure 1: Left: *Effective Surface temperatures of isolated Neutron Stars:* Observations of effective surface temperatures of several isolated Neutron Stars compared with theoretical cooling curve (T_{eff}) calculated for a distant observer. A non-superfluid NS model was used. Right: *Neutron Star cooling over time.* A description of Neutron Star cooling over time where internal temperature, surface temperature, neutrino, photon and total luminosities (redishifted for a distant observer) are shown and a non-superfluid NS model was used. After the initial relaxation stage, the star enters the neutrino emitting stage, where the neutrino luminosity is high and the star is mainly be cooled by emitting neutrinos. This stage can last between 10^5 and 10^6 years. Not until the neutrino luminosity sufficiently drops does photon emission become the dominant mode for energy transfer.

detrimental to our understanding of the physics of highly dense matter. In this paper, we outline the general cooling process of a Neutron Star, discussing various theoretical and observational cooling mechanisms .We discuss their dependence on mass, time dependence, and the limits of theoretical and observational results.

Neutron Stars are composed of an atmosphere, crust, inner core and outer core. The crust is generally about 1 km thick, where a liquid ocean layer (1-100 meters thick) on the surface of the crust may be present. At the surface of the star, proton fraction is highest and nuclei with high densities of neutrons float in a sea of relativistic electrons, eventually giving way to free neutrons as you move deeper into the core. When the neutron drip density is surpassed it is favorable for neutrons to drip out of the nucleus, creating layers of fluid neutrons around strands of highly neutron-rich nuclei. The temperature of the crust is cooler than the core, with the exception of the initial stage of neutron star cooling (the first few seconds to years of the NS lifetime) where the crust has a higher temperature [2]. The outer core consists of densely packed neutrons, with some protons, electrons, and possibly muons still present in small fractions, with decreasing proton fraction as you move towards the interior of the star. The outer and inner cores make up the majority of the mass of the star, with the crust only contributing less than 10% of a solar mass. As densities near and surpass $2\rho_0$ where ($\rho_0 = 2.8x10^{14}$ g m c^{-3}) is the density of saturated nuclear matter, the inner core is formed, and little is known about the inner core at these extreme densities. The composition of the inner core is still unknown, and is the subject of relentless study. It is postulated that the inner core may contain other particles, including pion condensates, quark matter, or a mixture of different phases; generally various models of the EOS of this dense matter give widely varying results. The inner core is not present for smaller neutron stars, which have cores resembling the outer core of a large NS.

1.2. The cooling life of a Neutron Star

In the first few seconds of a newly born neutron star, the core and interior are initially opaque to neutrino emission, and the star is more than 500 billion K, (20-50 MeV). After about 30 seconds, the newly born star becomes transparent for neutrinos and quickly cools, releasing neutrinos from its hot crust and core. During the early thermal relaxation phase which is in the first first few decades of the life of the star, it cools from more than 100 billion K to a few hundred kelvin.

After the initial cooling stage, in the next million years the star will mainly cool by emitting neutrinos. In this stage, the highly conductive core has reached a thermal equilibrium and can be described by a bariotropic EOS. (In this state the effective surface temperature reflects the thermal state of the core.) This stage can last between 10^5 and 10^6 year. Larger masses, neutron stars might have a longer period of neutrino emission. In this stage, the star undergoes rapid cooling due to the direct Urca processes, which will be discussed in section 2.

In the final stage of neutron star cooling, interior temperatures reach 10^6 K and photon emission dominates over neutrino emission, which is slow due to a low proton fraction. The dominant thermal process is heat transport to the surface, resulting in the thermal emission of photons.

Yakovlev, et al. (2004) summarizes various observations of effective surface temperatures of several isolated Neutron Stars compared with theoretical cooling curves (T_{eff}) calculated for a distant observer in 3. A non-superfluid NS model was used. Only an upper limit was determined for the two youngest sources. T for the next five sources, with ages $10^3 < t < 10^5$ years, have been obtained. Their thermal radiation spectra were fit with hydrogen atmosphere models, which prove a better theory than blackbody models for these sources. [2]

Also shown is theoretical results for internal temperature, surface temperature, neutrino, photon and total luminosities (red shifted for a distant observer) which are shown for the same NS model. After the initial relaxation stage, in the next million years the star will enter the neutrino emitting stage, where the neutrino luminosity is high and the star is mainly be cooled by emitting neutrinos. This stage can last between 10^5 and 10^6 years. Not until the neutrino luminosity sufficiently drops does photon emission become the dominant mode for energy transfer. At this stage, much slower (standard) cooling processes dominate, which drop the rate of cooling by orders of magnitude and will be discussed in section 2.

2. Theoretical Cooling Calculations

2.1. Thermal Conductivity and Heat Capacity

The two main factors contributing to the cooling theory are the neutrino emissivity Q, heat capacity C_v, and thermal conductivity of neutron star matter. General relativistic corrections for standard heat equations in the interior of a star can be solved to determine effective temperature and effective surface temperature (T_s) for the neutron star, as derived in [3]. The NS thermal luminosity is:

$$L = 4\pi\sigma R^2 T_s^4(t) \tag{1}$$

where L refers to a locally-flat reference frame on the NS surface.

The apparent luminosity to a distant observer and apparent effective temperature to the distant observer can be described with:

$$L^\infty = L(1 - r_g/R) \tag{2}$$

$$T_s^\infty = T_s\sqrt{1 - r_g/R} \tag{3}$$

where $r_g = 2GM/c^2$ is the Schwarzschild radius [4].

The equation of state and composition of the neutron star core will affect neutrino emission mechanisms. Additionally, superfluity and the presence of strong magnetic fields can affect neutrons star temperature. These factors affect the thermal conductivity and the relation between the internal surface temperature of the star, and will be discussed in section 3.

The inner crust of a neutron star is characterized by the presence of free neutrons, and interactions can no longer be considered point-like due to the high density and corresponding relatively small distance between particles. A basic formula for heat capacity can be determined by considering that the neutrons are strongly degenerate almost everywhere in the neutron star. The Summerfield result

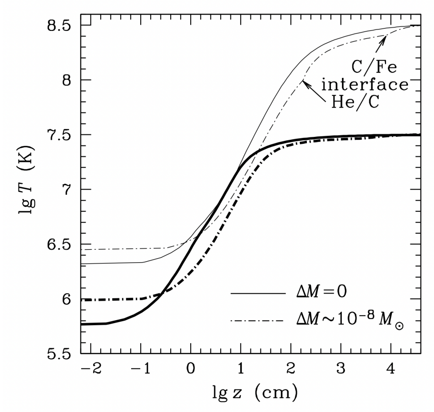

Figure 2: *Temperature versus depth (z) in the NS envelope .* Temperature versus depth (z) in the NS envelope for two internal temperatures: $10^{8.5}$ K (light curves) and $10^{7.5}$ K (heavy curves), for nonaccreted and accreted envelopes. In this paper we focus on isolated Neutron Stars (the solid lines). The effect of lighter accreting elements is a more heat transparent envelope due to lighter elements having a higher thermal conductivity. The star in question is a massive neutron star (M = 1.4) and (r = 10 km).

for fermi gas at $T << \epsilon F$ is usually applicable where X stands for the fermion type.

Additionally, the heat conduction in the core has the following values for particle contributions to thermal conductivity:

$$k_n = \frac{\pi^2 T n_e \tau_n}{3m_n^*)} \tag{4}$$

$$k_p = \frac{\pi^2 T n_p \tau_n}{3m_p^*)} \tag{5}$$

per unit volume [4].

We can compare, theoretical cooling curves to observations to determine constraints on the equation of state.

2.2. *Main cooling Mechanisms*

Theoretical mechanisms for neutron star cooling can be divided into two main regimes: enhanced (fast) cooling, and standard (slow) cooling. The faster method of neutrino cooling corresponds to the direct Urca process, which was investigated by Edward Brown in 2016 [5]. The Direct Urca (a.k.a. Durca) process is a method of neutrino cooling, believed to occur early in all neutron star lifetimes and may occur later in a few heavier neutron stars. In the direct Urca process, thermally excited neutrons undergo beta decay releasing protons, electrons, and antineutrinos while thermally excited protons undergo the reverse reaction. This process requires a high proton fraction of ($Y_e \geq 1/9$), and thus is not maintained for the entirety of the star's lifetime. To test for the direct Urca process, one can determine the temperature and age of isolated thermally emitting neutron stars. By comparing a star's temperature with predictions from theoretical models, we can infer whether rapid cooling occurred in the star's early life. Some results may suggest that a handful of stars underwent enhanced cooling early in their lifetime [5].

For a typical neutron star, maintaining a sufficient proton fraction is difficult and long after the initial star collapse most do not cool using the direct Urca process but rather a modified (Murca) process where an additional particle acts as an intermediary for the reaction. This process is more than one million times slower, resulting in more gradual (standard) cooling [7, 5] and allowing for other small cooling processes to dominate. Generally at this point the neutrino luminosity has sufficiently dropped to allow for the dominant cooling effect of photons emitted from the stars surface. For some stars which are sufficiently massive, it is postulated that the direct Urca process may continue after this time, however, most stars devolve into these lower cooling processes after a few thousand to a few million years. If direct Urca processes are forbidden, the other reactions become relevant like Bremsstrahlung processes and produce a slow cooling. Because neutron stars do not produce energy of their own, they burn slowly, analogous to an ember after a fire and can cool for millions to billions of years.

2.3. *Superfluidity*

When a component of the neutron star matter becomes superfluid, its specific heat is strongly altered. When T reaches the critical temperature (T_c) for the pairing phase transition, the heat capacity jumps by a factor of two. However, as temperatures continue to decrease, the superfluidity reduces the emissivity of these usual neutrino reactions, causing the heat capacity to become suppressed. In some cases superfluidity can increase cooling due to a specific pair breaking information neutrino emission mechanism (PBF) [8]. Observations of CXO

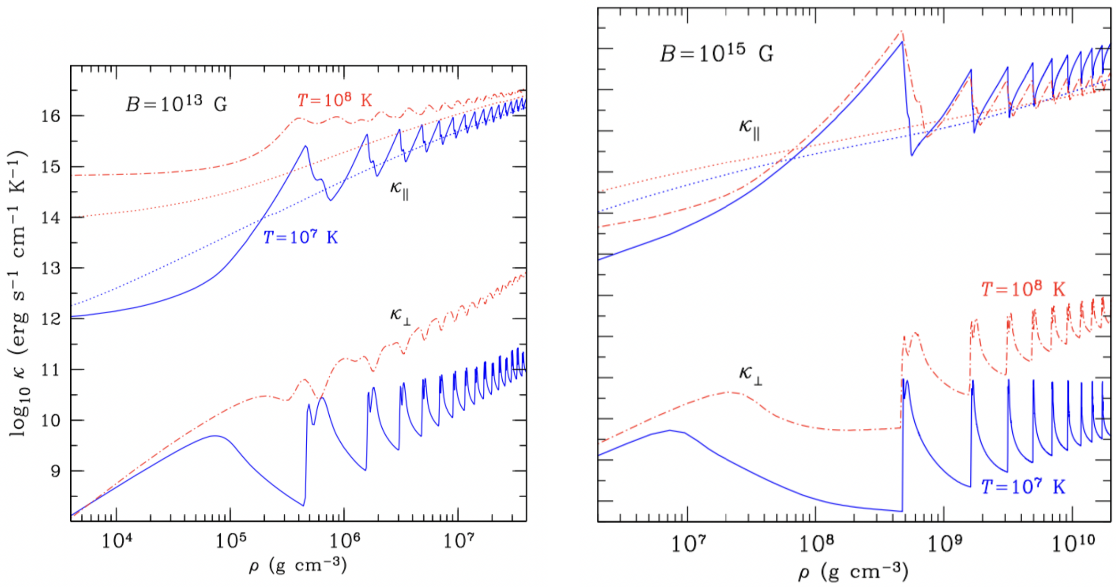

Figure 3: Left: *Electron thermal conductivities along a B field for two magnetic field strengths.*. A plot of electron thermal conductivities along a B field are shown for magnetic field $B = 10^{13}$ G (left panel) and 10^{15} G (right panel) as functions of mass density at temperatures T = 10^7 K (solid lines) and 10^8 K (dot-dashed lines). The non-magnetic thermal conductivities are shown by the dotted lines for reference. Each peak in the graph corresponds to the filling of the first and subsequent Landau levels, where the cyclotron orbits of electrons are quantized in the presence of the neutron star's magnetic field. The distinction between the higher and lower curves is a calculation along (parallel to) the B-field (upper curve) as opposed to across it (lower curve).

J232327.9+584842 in the Cassiopeia A supernova remnant (abbreviated Cas A NS) showed an unexpectedly high temperature decline over several years, which can be explained by PBF [10], although alternative theories have been proposed. In non-superfluid cases, neutrino luminosity of the NS is dominated by the core emission, simply because the core comprises the majority of the total neutron star mass. However, the crust contribution to neutrino emmissivity may prevail in the case of strong superfluidity in the core, because neutrino emissivities in the core are suppressed in that case.

2.4. The Influence of a Magnetic Field

Magnetic fields ($B > 10^{14}$ G) are strong enough to noticeably heat up the crust and power observed x-ray radiation. Additionally, the cooling timescale for strongly magnetized neutron stars is several times larger than for weakly magnetized ones. Additionally, under the influence of a strong magnetic field, the effective local surface temperature Ts is non-uniform and depends on the magnetic field geometry. In general, it is currently thought that magnetic fields may be the cause for higher than expected temperatures of neutron stars with extremely high magnetic fields. A neutron star may be heated from the inside, due to dissipation of a strong, magnetic field. (It has been suggested that dissipation of extremely strong magnetic fields could be responsible for high effective temperatures of magnetars) [7]. In theoretical simulations, the inclusion of the magnetic field and calculations explains objects with the highest luminosities. The effect of extremely strong, magnetic fields, (for example, greater than 10^{17} G), may alter the mechanical structure of the neutron star, which was previously assumed to be spherical, altering thermal properties [7].

The effects of a strong magnetic field on NS cooling are complex, and quantum effects must also be considered. In figure 3, a plot of electron thermal conductivities along a B field are shown for magnetic field $B = 10^{13}$ G (left panel) and 10^{15} G (right panel) as functions of mass density at temperatures $T = 10^7$ K (solid lines) and 10^8 K (dot-dashed lines). The non-magnetic thermal conductivities are shown by the dotted lines for reference. The ρ-dependence of the thermal conductivities is shown, and each peak in the graph corresponds to the filling of the first and subsequent Landau levels, where the cyclotron orbits of electrons are quantized in the presence of the Neutron Star's B-field. The distinction between the higher and lower curves is a calculation along (parallel to) the B-field (upper curve) as opposed to across it (lower curve).

3. Conclusion

Although we know very little about the interiors of Neutron Stars, there are many tools that we can use to study and approximate neutron star cooling which compare with observations. In this paper, we outlined the general cooling process of a Neutron Star, discussing various theoretical and observational cooling mechanisms including the direct and modified Urca processes. We discuss their dependence on mass, time dependence, and the limits of theoretical and observational results as well as NS cooling curves. Over the life of a Neutron Star, we saw that it undergoes three main stages of cooling which have a strong dependence on mass and well explain observed values of emission and luminosity. We found that NS cooling has a strong dependence on other factors like superfluidity as well as the presence of a magnetic field.

There is much to be gained from understanding Neutron Star cooling including understanding NS x-ray emission, determining the radius of the star, and constraining the Nuclear Equation of State (EOS). Understanding Neutron Star development and cooling stages has implications for understanding the properties of superdense matter under extreme conditions, an unresolved problem in astrophysics with the potential to better understand the nature of fundamental particles. Additionally, a better understanding of the effective temperatures of Neutron Stars can help us hone in values for certain star distances and radii, which are still unknown.

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