# Structure of Neutron Stars

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## 1 Overview of Neutron Stars

Neutron stars are some of the strangest objects in the universe, containing the densest form of matter that can be studied. When a star with a solar mass within the range of 8 to $20M_{\odot}$ leaves the main sequence, this star will become a red giant and then a supergiant, increasing in luminosity and decreasing in temperature. Once there is no more nuclear fusion within the core, the star will go supernova (either type Ib, Ic, or II), outputting large amounts of neutrinos and a shocking amount of energy. During this process, the star's core collapses under immense gravity while protons and electrons are forced to come together to form neutrons, the primary component of neutron stars. After the core collapse, the mass of a neutron star is within the range of 1 to $2M_{\odot}$, and the radius is within 10 to 20 kilometers (Vidana, 2018). A neutron star will form when the solar mass is too large to form a white dwarf but too small to form a black hole. Neutron stars are observed in all bands of the electromagnetic spectrum, using ground and space telescopes, and can form binaries with other neutron stars (including pulsars and magnetars) and even black holes.

- Neutron stars are the densest observable objects, aside from black holes, with an average density of $10^{15}$ g $cm^{-3}$
- Neutron stars have the largest surface gravity that is currently known with a gravitational acceleration of roughly $10^{14}$ cm $s^{-2}$ (which is roughly $10^9$ times g)
- Neutron stars have the largest magnetic field strength that has been observed with a maximum strength of roughly $10^{15}$ G
- Neutron stars are the highest temperature superconductor with a critical temperature of roughly $10^9$ K
- The highest temperatures observed in the universe, aside from the Big Bang, are observed during the birth of neutron stars with a temperature of $7 \times 10^{11}$ K

## 2 History of Neutron Stars

The history of neutron stars spans the last century:

**1920** Ernest Rutherford predicted the existence of neutrons while studying atom structure.

**1931** Landau predicted the existence of stars that were more dense than white dwarf stars, but there was no evidence for this yet.

**1932** James Chadwick discovered the neutron.

**1934** Baade and Zwicky claim that neutron stars were the result of supernovae.

**1964** Hoyle, Narlikar, and Wheeler predict that neutron stars rotate.

**1965** Hewish and Okoye observe a powerful radio signal coming from the crab nebula, confirmed to be a neutron star in 1968 whose pulse period appeared to be increasing. The term pulsar was first used to describe these neutron stars.

**1974** Hulse and Taylor discovered the first binary pulsar, PSR 1913+16 and they were awarded the Nobel Prize in Physics in 1993. This discovery further led to gravitational wave detections for neutron stars.

**1998** Kouveliotou discovered the first magnetar.

## 3 Types of Neutron Stars

**Pulsars** The most common type of neutron star is a pulsar. A pulsar is a rotating neutron star that has been highly magnetized and emits beams of electromagnetic radiation that can be observed from Earth (Vidana, 2018). These neutron stars are the fastest-spinning macroscopic objects in the universe although their spin slows over time due to energy loss. One example is PSR J1748-2446ad in globular cluster Terzan 5 which has a spin rate of 714 Hz meaning that this pulsar has a surface velocity of roughly c/4 (Lattimer, 2015).

**Magnetars** These neutron stars have an even more powerful magnetic field, emitting immense amounts of x-ray radiation. While an average neutron star has a magnetic field on the magnitude of $10^{10}$ G, magnetars have a magnetic field on the magnitudes of $10^{13}$ to $10^{15}$ G.

**Millisecond Pulsar** These pulsars have a very short rotational period of 1 to 30 ms. Because these neutron stars are often found in binaries, their rotation begins to speed up when they gain mass, and therefore angular momentum, from their companion star. Still, their rotation pulses are very stable (Perrodin & Sesana, 2018).

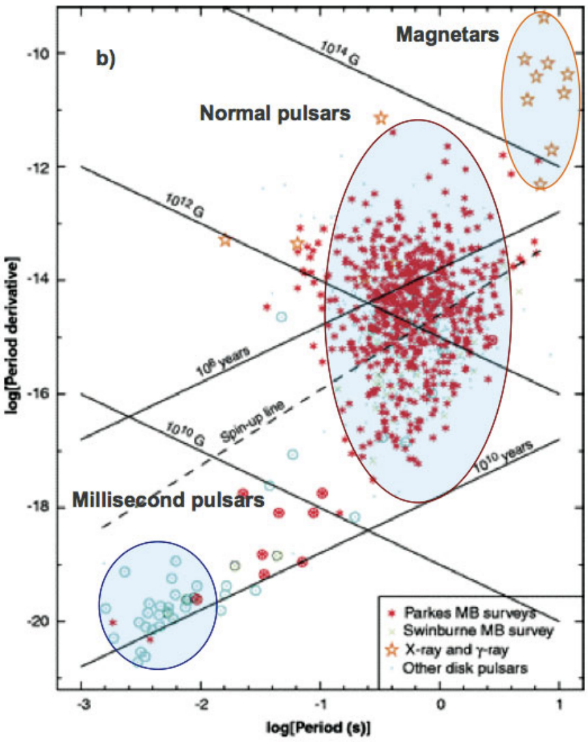


Figure 1: This figure shows the period distribution of each main type of neutron star. It can be seen that normal pulsars are the most common and magnetars and millisecond pulsars are observed less frequently. Magnetars are observed to have the longest period and millisecond pulsars are observed to have the shortest period. Image retrieved from Vidana (2018).

# 4 Structure of Neutron Stars

There is a large amount of information about the structure of neutron stars that is heavily based on theory alone, due to how bizarre these astronomical objects are. Like other stars, neutron stars are observed to have a stellar envelope and it can be assumed that neutron stars have a crust-like region because observers witness starquakes and changes in magnetic field. Similarly, it would follow that neutron stars also have a very dense core due to their immense gravity but due to the strange nature of this dense matter (likely composed of "nuclear pasta") and observational limitations, it is difficult to make certain conclusions at this time.

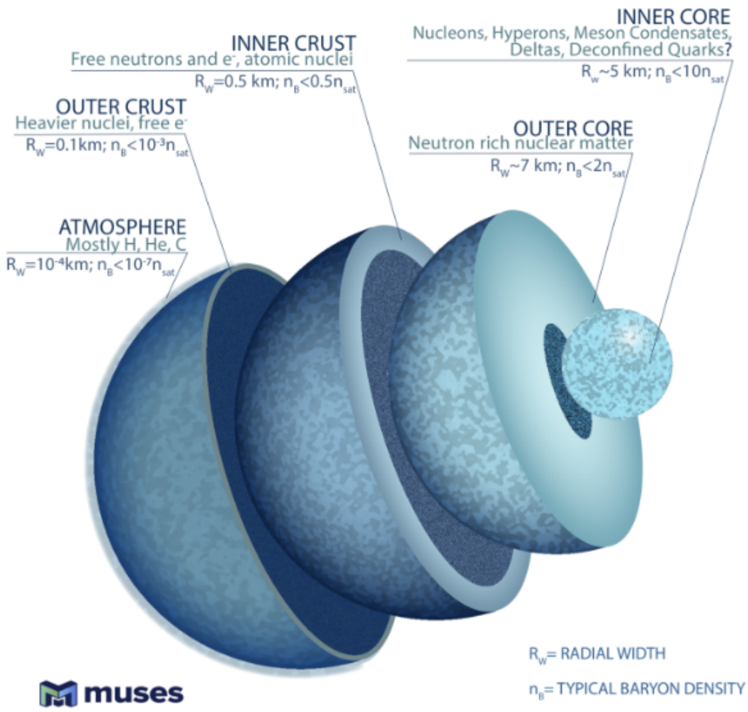


Figure 2: This figure displays the different regions of a neutron star: atmosphere, outer crust, inner crust, outer core, and inner core. Included are the main components of each region along with the radial width and the typical baryon density. Diagram retrieved from the Muses collaboration with the University of Illinois Urbana-Champagne

## 4.1 Envelope

A heat blanketing (thermally insulating) envelope, like those of neutron stars, is a very thin region with a mass of only $10^{-6}$ $M_\odot$ and represents a very different temperature on the surface that exists internally (M.V. Beznogov, 2021).

**Atmosphere** The atmosphere of a neutron star is mainly composed of ionized lighter elements such as Hydrogen, Helium, and Carbon although the exact composition is unknown. Different ratios of these elements have been detected with different neutron stars (M.V. Beznogov, 2021). This Hydrogen and Helium may also be left over from active accretion stages involving a stellar companion.

**Ocean** This is the layer of liquid and gaseous ions that exist above the crust of the neutron star but it is sometimes considered to be a part of the outer crust due to the excess of ions and electrons. The composition of this layer is typically very dense with neutrons that are essentially locked into place by neutron degeneracy pressure.

## 4.2 Crust

### 4.2.1 Outer Crust

The outer crust of a neutron star is essentially a reflection of the core of the star before the core collapses. This means that the outer crust is primarily composed of a lattice of heavy metals like Iron and Nickel, considering that a supernova occurs when the star has a fully Iron core and therefore stops fusing elements. This region continues inward until the nuclei become unbound at the neutron drip density ($\rho = 4 \times 10^{11}$ g $cm^{-3}$) and the sea of electrons becomes so energetic that inverse beta decay occurs and an electron and a proton form a neutron and a neutrino (M.V. Beznogov, 2021).

### 4.2.2 Inner Crust

The inner crust of a neutron star extends from the neutron drip density to the crust-core interface which has a density on the order of $10^{14}$ g $cm^{-3}$. In this region, many neutrons are free and the electrons are mainly degenerate and relativistic (C. Mondal, 2020). The composition of the inner crust influences the movement of heat and magnetic flux and therefore the inner crust affects starquakes and oscillation rates, including glitches. Some nuclear pasta may be present at the base of the inner crust of the neutron star (Zach Meisel, 2018). Nuclear pasta is a theoretical type of degenerate matter that exists in odd structures, resembling pasta shapes. Any space between nuclei or neutrons that typically exists due to the electron clouds, is no longer available, as all the electrons have been stripped off their atoms long before reaching the core, and protons are outnumbered by neutrons. Because of this, protons no longer have enough power to maintain the state of the nucleus and therefore these neutrons are able to rearrange themselves to form cylinders (nuclear spaghetti) or sheets (nuclear lasagna). This nuclear pasta is considered to be one of the strongest materials in the universe which means it can resist the gravitational force of the neutron star, resulting in slight imperfections to the spherical shape of the crust. These imperfections contribute to the small gravitational waves output by neutron stars as they spin.

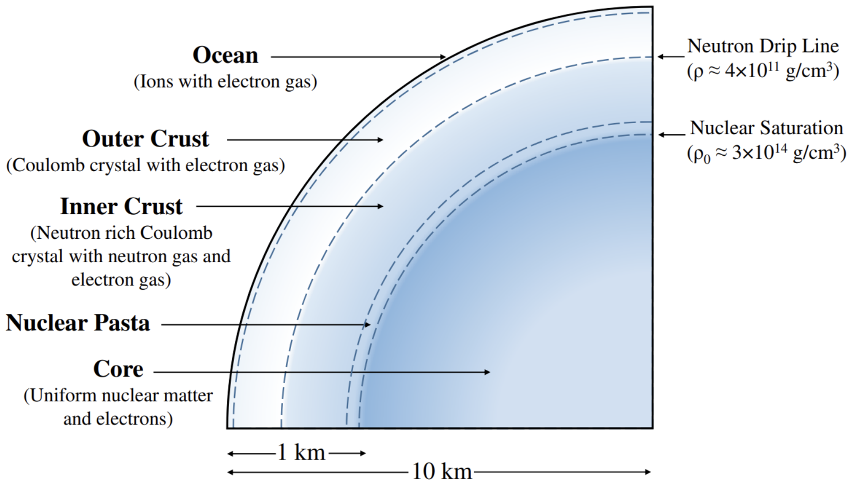


Figure 3: Image showing the outer layers of a neutron star with more detail, separating the envelope of the NS into the atmosphere and the ocean. Image retrieved from Caplan and Horowitz (2017)

## 4.3 Core

What is considered known about the core of a neutron star is still *very* theoretical and is hypothesized to contain some of the strangest matter in the universe. Continuing deeper into the core, this matter becomes a superconductive neutron fluid that is responsible for many of the properties of a neutron star (Mondal & Gulminelli, 2022).

### 4.3.1 Outer Core

As the almost pure neutron superfluid becomes more and more condensed as gravity increases towards the center, "empty" space becomes incredibly scarce (S. Gandolfi1, 2014). Any protons that still remain

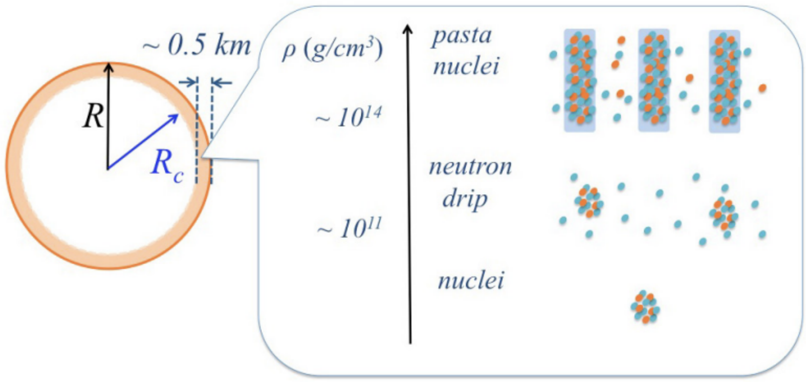


Figure 4: This graphic displays the differences in matter through the different regions of a neutron star, getting closer to the core. Graphic shows the state of the matter and the estimated densities associated with each state. Image retrieved from Gordon Baym (2018)

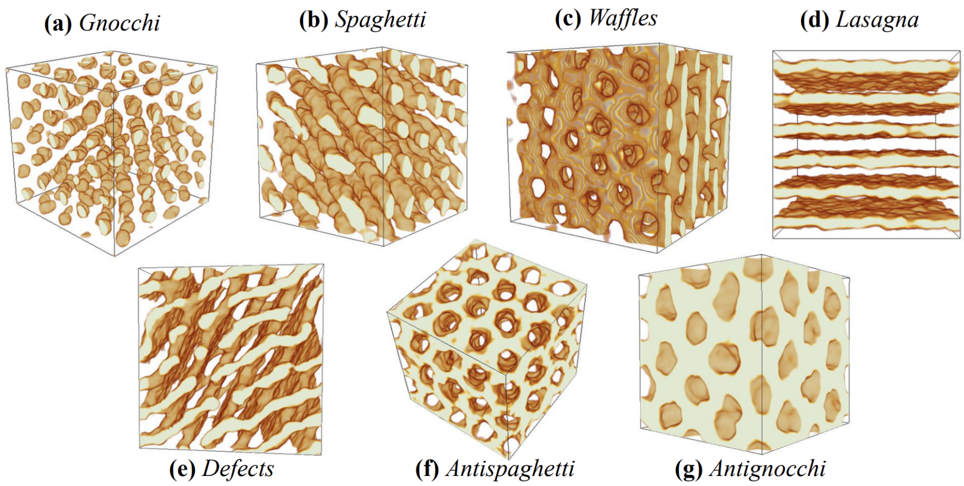


Figure 5: This diagram siaplays the different types of nuclear pasta and their shapes. Diagram retrieved from Caplan and Horowitz (2017)

in this material form a superconductive fluid. Small amounts of electrons and muons are present in order to keep a neutral charge in the core. The superfluid interacts with the inner crust (specifically the nuclear pasta) contributing to the imperfect shape of the neutron star, leading to the production of the small gravitational waves. Although these gravitational waves should be able to be detected, observers have had no luck observing them due to the low strength of their signal, especially compared to larger astronomical events such as NS-NS or NS-BH mergers.

#### 4.3.2 Inner Core

The inner core of a neutron star is hypothesized to be composed of neutrons and quark matter. Neutrons are thought to dissolve into up, down, and strange quarks, creating quark-gluon plasma. Spin 1/2 neutrons combine to form Cooper pairs (a pair of fermions) which form bosons, spin-0 and spin-1 particles. It is because of these pairs that the core of the neutron star is an extremely powerful superconductor (Wood & Graber, 2022), which contributes to the strength of its magnetic field. In addition to these phenomena, neutrons are thought to be accompanied by hyperons which are a type of baryon with at least one strange quark. The best assumption for the contents of the core of a neutron star is that there is some quark matter that is stronger than anything that can be replicated on Earth (Gordon Baym, 2018) and because of this, it is difficult to be certain about the contents of the inner core.

# 5 Conclusion

Neutron stars are some of the more bizarre astronomical objects within our universe, but they are incredibly dense and hot with intense magnetic fields. Being born from a star with a solar mass of 8 to $20M_{\odot}$, the 1 to $2M_{\odot}$ neutron stars are incredibly dense, making them the home of unique matter that cannot be observed in other objects. The structure of neutron stars is made up of the envelope, the crust (inner and outer), and the core (inner and outer). Each region has its own unique composition with not only different elements but different states of matter. The envelope and the crust somewhat resemble the remnants of the star that went supernova, with classic nuclei that begin to behave strangely due to the intense gravity. The core of a neutron star is still highly theoretical but is considered to be made up of neutrons and/or quark matter. This quark matter contains up and down quarks which are the most common but also contain strange quarks that do not typically exist in a steady state in our known universe. As astronomers continue to discover more about neutron stars, more information about these strange forms of matter may be realized and secrets of the start of our universe may be revealed by examining their cores.

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