The structure of a Neutron Star and how to find it

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Abstract:

Neutron stars are formed when the remnant of a massive star collapses gravitationally following a supernova explosion, assuming the star isn't too massive to produce a black hole. The very central region of the star – the core – collapses, crushing together every proton and electron into a neutron. These extreme objects measure between 10 and 20 km across and have densities of 10^{17} kg/m^3 and magnetic fields up to 10^{11} T. These intense conditions produce strong beams of electromagnetic radiation which sweep across our skies as cosmic lighthouses. In this report, I will review its formation, internal structure, and how it is found. I will also cite and explain a few of the recent relevant research.

1. Introduction :

The stars that eventually become neutron stars are predicted to have a mass of 8 to 20-30 times that of our sun when they first form. These figures are likely to change as supernova simulations improve, but it appears that a star with an initial mass of less than 8 solar masses becomes a white dwarf, and a star with an initial mass of more than 20-30 solar masses becomes a black hole. The basic idea is that when the central part of the star fuses its way to iron, it can't go any farther because at low pressures iron-56(^{56}Fe) has the highest binding energy per nucleon of any element, so fusion or fission of iron-56(^{56}Fe) requires energy input. As a result, the iron core keeps accumulating until it gets to about 1.4 solar masses("Chandrasekhar mass") at which point the electron degeneracy pressure that had been supporting it against gravity gives up and the star collapses inwards.(1)

$$M_{\text{limit}} = \frac{\omega_3^0 \sqrt{3\pi}}{2} \left(\frac{\hbar c}{G}\right)^{\frac{3}{2}} \frac{1}{(\mu_e m_H)^2} \qquad (1)$$

Where h is Planck's constant, c speed of light, G gravitational constant, μ_e is the mean molecular mass, m_H mass of hydrogen.

First confirmed by Hewish and Bell in 1967 neutron stars rotate extremely rapidly as a consequence of the conservation of angular momentum, and have incredibly strong magnetic fields due to conservation of magnetic flux which funnel jets of particles out along its magnetic poles. These accelerated particles produce very powerful beams of light which are observed as pulsars. (2)

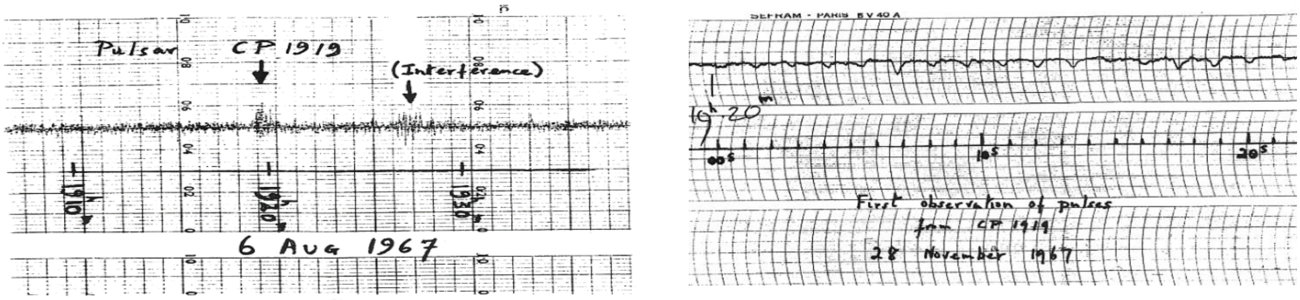

Figure 1: The pulsar CP1919 (for Cambridge Pulsar at **right ascension** α=19h19m). Image credit: Jocelyn Bell Burnell and Antony Hewish.

Since neutron stars began their existence as stars, they can be found all around the galaxy in the same places where we can find stars. They can be discovered alone or in binary systems with a companion, just like stars.(3) However, since they don't produce enough radiation, many neutron stars are likely undetectable. They can, however, be seen under specific circumstances. A handful of neutron stars have been discovered silently releasing X-rays at the centers of supernova remnants.

At their birth neutron stars can rotate at least 60 times every second. If they're part of a binary system, they can boost the rotation rate to around 600 times per second by accumulating material. Neutron stars that have lost energy through radiative processes have been observed to rotate as slowly as once every 8 seconds while still emitting radio pulses and neutron stars in X-ray systems have been observed to revolve as slowly as once every 20 minutes. Observations also show that the rotation rate of isolated neutron stars fluctuates slowly over time, often decreasing as the star ages and rotational energy is lost to the magnetic field (though occasionally glitches are seen).(4)

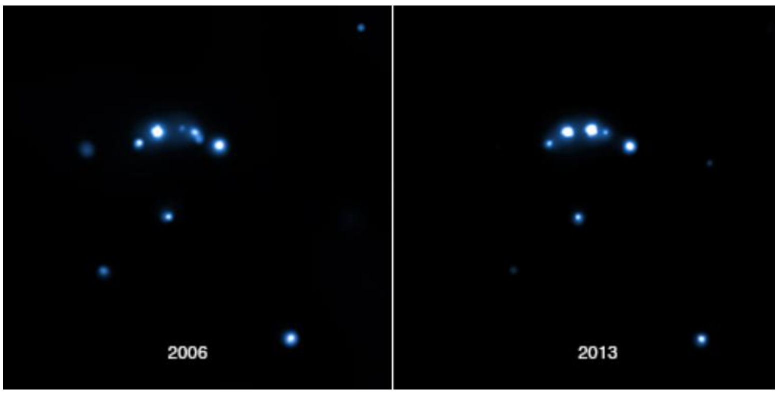

Figure 2: These two images from NASA's Chandra X-ray Observatory show a large change in X-ray brightness of a rapidly rotating neutron star, or pulsar, between 2006 and 2013. The neutron star - the extremely dense remnant left behind by a supernova - is in a tight orbit around a low mass star. This binary star system, IGR J18245-2452 is a member of the globular cluster M28(credits : NASA Chandra X-ray)

A composition of neutrons may seem surprising if you consider that free neutrons decay with a half-life of about 15 minutes by the reaction

$$n \to p + e^- + \bar{\nu}_e. \quad (2)$$

Yet neutrons can exist stably in an atomic nucleus or a neutron star. The reason is that the reaction is in equilibrium with the reverse reaction, electron capture on protons

$$p + e^- \to n + \nu_e. \quad (3)$$

The condition for equilibrium is that the balance of the chemical potential

$$\mu_n = \mu_e + \mu_p. \quad (4)$$

This is known as beta-equilibrium.

The structure of a neutron star can be divided into four layers. An outer crust is made up of atomic nuclei and free electrons that extend from the surface and have a thickness of a few hundred meters. There is only one tonne per cubic centimeter density there. The inner crust is the next layer, where free neutrons combine with atomic nuclei and free electrons form a solid layer. An outer (liquid) core exists further down, where unbound electrons, neutrons, protons, and muons coexist in a nuclear soup.(5) Finally, the density rises to the point where describing particle interactions becomes difficult due to our limited understanding of the strong force at these densities [recall that the strong force is responsible for the interaction between quarks in nucleons as well as the existence of the nuclear force that holds atomic nuclei together]. The inner core, a mysterious zone where fundamental particles act in unanticipated ways, begins at this point. The densest place in the observable Universe is the inner core of neutron stars, with densities estimated to be around a billion tonnes per cubic centimeter.

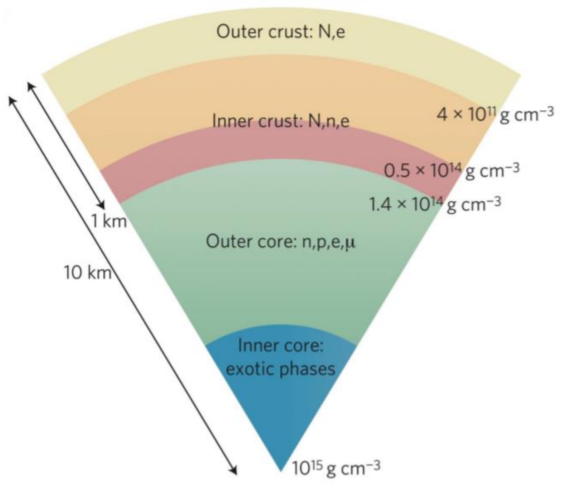

Figure3: The neutron star structure showing the different regions of the crust and core.

In the upcoming sections, we will break down the structure of the neutron star starting right from its outermost magnetosphere, crust, inner section, and finally the core. Some work that goes on to explain its internal structure will also be cited and explained. Finally, I will end with pulsars and magnetars which help us to detect them.

2. The Magnetosphere

This is the first thing that we would encounter if we were to approach a neutron star. This is quite literally the strongest magnetic field in the universe. Even the weakest neutron star fields are a billion times stronger than those of the Earth or Sun. This magnetosphere is very different than the magnetized space around the Earth or the Sun. It's filled with electrons and positrons. These matter-antimatter pairs are created out of the extreme energy photons in the magnetic field. This field then essentially becomes a particle accelerator with electron current flowing in one way and positron current flowing in the other way due to their opposite electric charges. These and other charged particles end up being blasted out along the poles of the magnetic field. Their motion in their jets results in radiation that we observe as pulsars.(6)

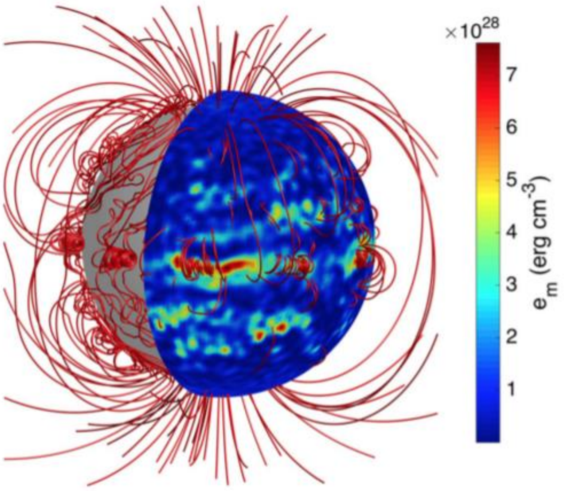

Figure 4: A snapshot from a 3D simulation of evolving magnetic fields in a neutron star crust. (K. N. Gourgouliatos, et al)

Neutron star magnetospheres are rooted in the unyielding crust and can be distorted by abrupt crustal disturbances (referred to as "starquakes"). The twisted magnetosphere does not stay static and progressively untwists, releasing magnetic energy and emitting radiation.(7) It's not obvious what mechanisms are capable of producing fields in the B $\approx 10^8$-10^{11} T range, but dynamo effect and magnetic flux freezing during the collapse are both likely candidates. Neutron star spin periods range from a few milliseconds to tenths of seconds over four decades. Charged particles are dragged into corotation with the star by the stellar magnetic field. Relativistic corotating speeds are reached at the light cylinder defined by :

$$r_L = \frac{c}{\omega} = \frac{c\,P}{2\,\pi} = 48\ \mathrm{km}\left(\frac{P}{1\ \mathrm{ms}}\right) \quad (5)$$

where c is the speed of light, P=2π/ω the period of the rotating neutron star(pulsar period) and ω its rotation rate. It is their compactness that places them closer to the black hole stage because

$$\frac{R_s}{R} = 0.345 \left(\frac{M}{1.4\ M_\odot}\right) \left(\frac{R}{12\ \text{km}}\right)^{-1} \tag{6}$$

Where $R_s = 2GM/c^2$ is the Schwarzschild radius, M and R are the neutron star mass and radius respectively, and G is the gravitational constant. Hence, neutron stars are therefore places where general relativity and quantum electrodynamics act together to sustain the extreme electromagnetic activity. This intense magnetic field can alter the vacuum itself. It provides space with weird quantum refraction properties. Light moving by this field may be deflected, split, or even recombined. (8)

3. The Atmosphere

As we peer through the magnetosphere we start to notice that the neutron star's surface is a little fuzzy. We are seeing the star's atmosphere, similar to the earth's atmosphere this layer of haze starts very tenuous almost like a vacuum, and gets denser as we drop, but the similarities end there. earth's atmosphere is mostly oxygen and nitrogen mainly in molecular form. Pressure increases as you go down so that at the earth's surface the weight of all that gas on top of our head is about 200 kgs. But the neutron's star atmosphere is not made of atoms, rather is a plasma in which atoms have been stripped of their electrons or ionized due to the extreme heat of around a million kelvin for a young neutron star. (9)Those nuclei are mostly hydrogen and helium captured from the near-space surrounding the star. While earth's atmosphere is something like 100 km thick depending on how you define the edge of space, the neutron star's atmosphere is barely a meter thick! Most of the plasma is confined within a thin shell 10 cm above the surface of the star due to its insane gravity which is almost 100 billion times the earth's gravity(100,000,000,000 g).

A pair of simple equations then defines how the density of the atmosphere has to rearrange itself with height above the surface so that gravity and pressure are always in balance. The equations look like this:

$$n(z) = n_0 e^{-\frac{z}{H}} \quad \text{where} \quad H = \frac{kT}{mg} \tag{7}$$

The exponential equation says that as you get farther from the surface, the density of the gas, N, drops very fast.

This thin layer of foggy plasma on the star's surface has a density many million times greater than anything on earth. It is here that we would start to encounter the truly strange states of matter. This matter is not all that different from a white dwarf.(10) In the dead core of a lower mass star like our sun, the plasma is crushed so tight that electrons are on the verge of overlapping. However, since the particles of the fermion family can't occupy the same quantum state, the matter becomes degenerate and thus electron degeneracy pressure stops the further collapse and ultimately holds the atmosphere up.

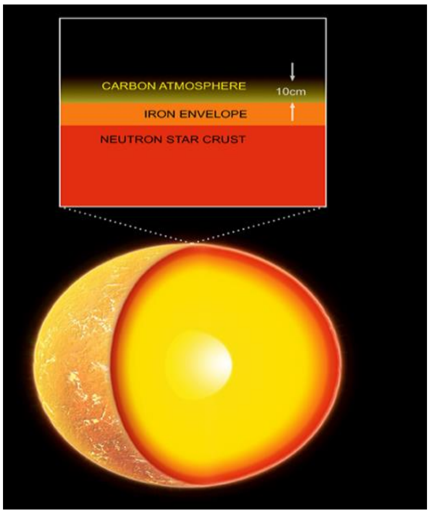

Figure 5 : Illustration of Neutron Star & Atmosphere
(Credit: Illustration: NASA/CXC/M.Weiss)

4. The Crust

Below this layer of plasma, there is a solid surface. It is made up of some crystalline material. However, that might be a bit counter-intuitive as we think of crystals as lattices of atoms connected by electron bonds. This crystalline material below the neutron star's atmosphere is frozen plasma in which its nuclei are locked together in a regular lattice. At these extreme densities($\sim 10^{11}$-10^{14} gm/cm^3) nuclei are pushed so close together that their mutual repulsion prevents nuclei from slipping past each other like gridlocks traffic.(11) The symmetry of that repulsion forces nuclei into a regular grid. In this case, the crystalline matter is mostly iron, which was the last element forged in the core of the star hours before it went supernovae.

4.1 The Outer Crust

Density only increases as we go down. The crystal lattice is fused with a gas of electron, so-called degenerate Fermi gas, which holds up this part of the star from collapse. The deeper we go the more energetic these electrons become. Soon these energies are high enough to drive some very exotic nuclear reactions. Electrons start to be driven into the iron nuclei in a process called electron capture. The negatively charged electrons merge with positively charged protons to produce neutrons. In this way, iron is converted into elements with fewer protons, which are still as heavy as iron but very neutron-rich. An example would be :

$$^{56}\mathrm{Fe} + e^- \rightarrow ^{56}\mathrm{Mn} \quad (8)$$

Going down a few hundred meters we would find nuclei that can’t even exist outside a neutron star. At such high densities(50 billion times the density of the earth) we might find a nucleus like zinc-80(^{80}Zn) which otherwise would decay in just 0.5 seconds on earth by ejecting neutrons. Nuclei with such high ratios of neutron to protons are only stabilized by the incredible pressures and extreme electron energies in the neutron star.(8)

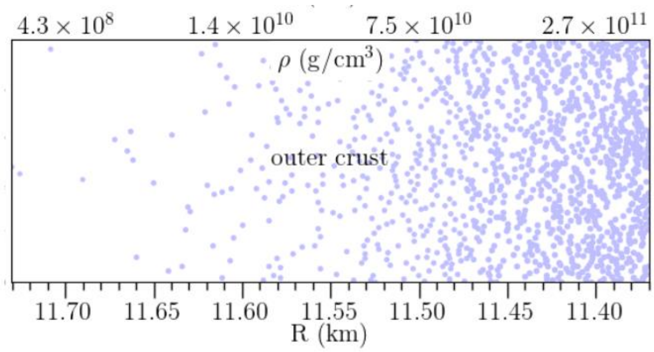

Figure 6: A figure visualizing the density of the outer crust of the neutron star(Andrew W. Steiner, 2020)

4.2 Inner Crust

As we leave the outer crust towards the inner crust, nuclei becomes so neutron-rich that they start to fall apart. This is called neutron drip. Neutrons leak from the nuclei into the ever-narrowing space between them. It's still not clear how deep this phenomenon begins but the best calculations suggest that it is quite close to 0.5 km from the surface where densities are now at least a trillion times the density of matter on earth. At this stage physicists just rely on theoretical calculations. We are beyond the point where we can duplicate these energies and these neutron-rich nuclei in particle accelerators. (12)As the neutron drip intensifies the space between the nuclei fills up with neutron gas while the electron gas gets thinner due to the electron capture process. The neutron gas stars take over the role of the electrons. Neutrons are also fermions so two of them can't occupy the same state, hence the star is now supported by neutron degeneracy pressure. Since neutrons can get much closer to each other before this degeneracy pressure kicks in hence much higher densities are possible.

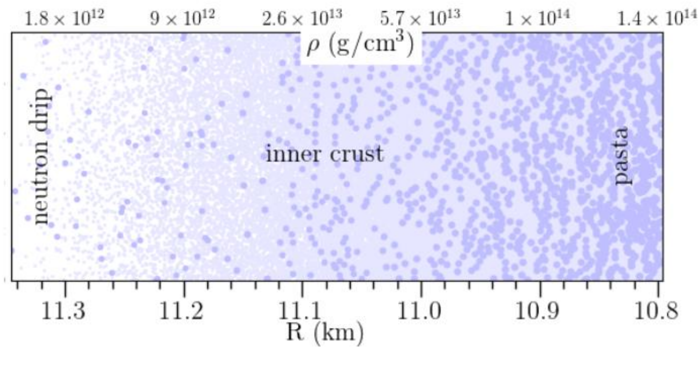

Figure 7: A figure visualizing the density of the inner crust of the neutron star(Andrew W. Steiner, 2020)

Further down the nuclei themselves start to get fuzzy protons are outnumbered by neutrons 5:1. A given neutrons wave function is so spread out that it becomes hard to even localize it inside of a given nucleus. By the time we reached the bottom of the crust around 1 km deep, densities have reached 100 trillion times that of the earth. Here the once distinct nuclei are beginning to touch each other.

5. The Nuclear Pasta

Nuclear pasta is a hypothetical kind of degenerate matter that is thought to exist within neutron star crusts. Nuclear spaghetti, if it exists, is the most powerful material in the universe. At matter densities of 10^{14} g/cm3, nuclear attraction and Coulomb repulsion forces are identical between the surface of a neutron star and the quark-gluon plasma at its core. Because of the fight between the forces, a variety of complicated structures made up of neutrons and protons emerge. Because the architecture of these structures resembles various forms of pasta, astronomers refer to them as nuclear pasta.(9)

This is perhaps the least known and the weirdest state of matter in the universe. When nuclei start to touch they rearrange forming exotic shapes. Nuclei have a sort of competition, while neutrons and protons feel a very strong short-range attraction to each other due to strong nuclear force the electric repulsion between the remaining protons tries to push them as far away from each other as they can. Down here there may be 20 neutrons for each proton, so the protons can't resist the forces reshaping nuclei.

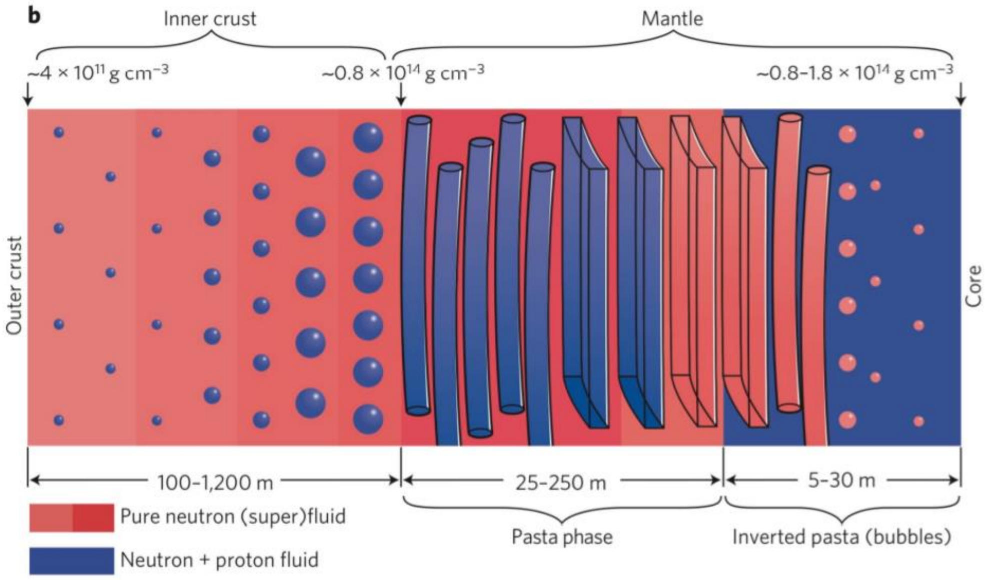

Figure 8: Nuclear pasta. Top: An illustration of the transition from normal nuclei through the pasta phases to the core. Lasagna formed in a molecular dynamics simulation. (C. J. Horowitz, et al)

5.1The Nuclear Spaghetti and Lasagna

With all this pushing and pulling we see a complete rearrangement of matter. Nuclei reform radically forming cylinders containing many millions of protons and neutrons. Nuclear physicist affectionately calls this phase of matter nuclear spaghetti. At slightly higher densities this nuclear spaghetti may be squeezed to form sheets called nuclear lasagna. Since this matter is so dense, it is really hard to bend and move this stuff. Nuclear pasta may even be the strongest material in the universe, almost a quintillion times stronger than steel!(11)

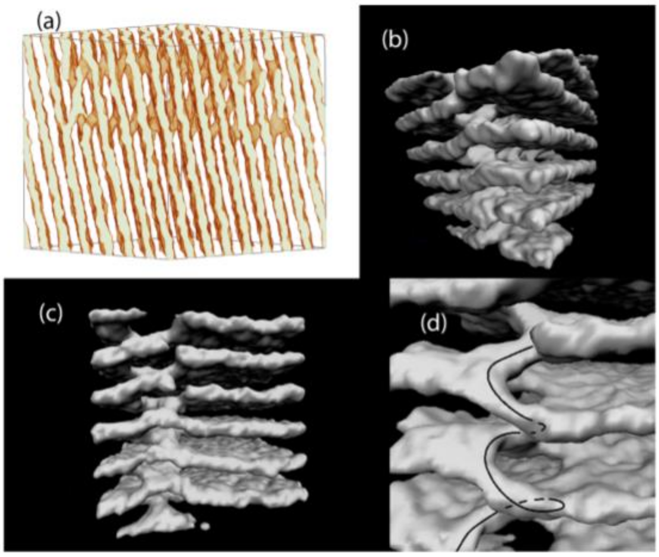

Figure 9: Lasagna formed in a molecular dynamics simulation. Spiral defects link the lasagna sheets. (C. J. Horowitz, et al)

The enormous strength of nuclear pasta allows it to resist the insane gravitational forces and so support a sort of jumbled texture sort of like nuclear pasta mountains buried beneath the surface of the star. These could be as tall as 10 cm which doesn't sound like a lot until you remember every cubic cm of nuclear pasta weighs as much as a mountain on earth! As the neutron star rotates buried neutron star mountain ranges get dragged in circles making a very weak gravitational weak signal. These gravitational wave signals are much weaker than the ones from neutron star and black hole mergers and hence are much harder to detect. However instead of being a big splash its continuous hum at exactly one frequency- twice the frequency of the neutron star's rotation. (12)

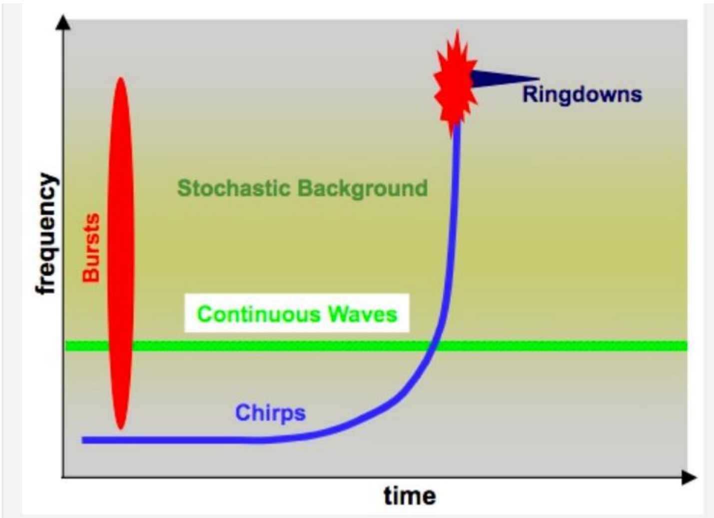

Figure 10: A schematic of frequency vs. time for different types of gravitational wave signals. Bursts are shown in red, continuous waves in green, chirps and ringdown in blue, and the stochastic background in yellow. (credits: LIGO and VIRGO)

Gravitational-wave astronomers are searching for these signals with LIGO right now. Targeting pulsars in our galaxy using their known rotational frequencies. They haven't found one yet, but they might soon, giving us a glimpse of the inner working of the neutron stars. By the time we reach the bottom of the pasta layer just above the neutron star core, all of that matter has been squashed together into a soup of mostly neutrons and just the occasional proton. The density here is 200 trillion times anything found on earth.(14)

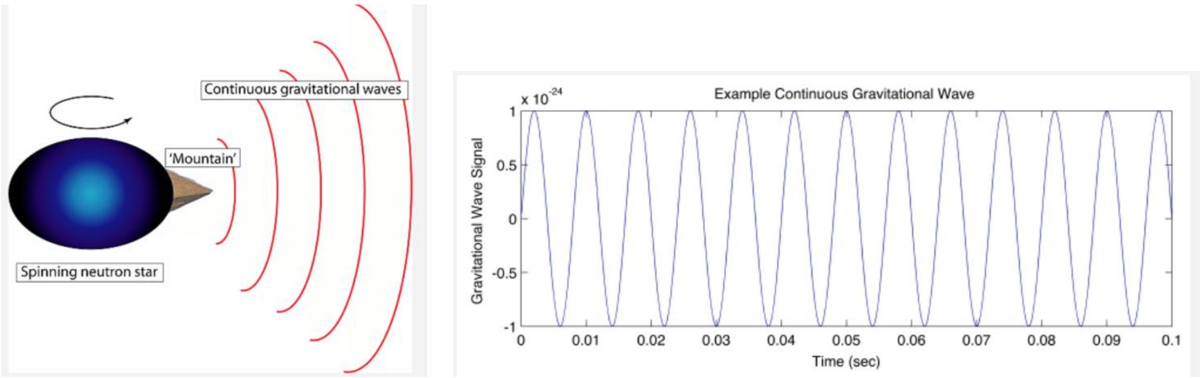

Figure 11: A cartoon figure showing the continuous emission of gravitational waves due to the neutron star mountain credits: LIGO and VIRGO

6. The Core

By the time we reach the bottom of the pasta layer just above the neutron star core, all of that matter has been compressed together into a "soup" of mostly neutrons and just the occasional proton. The density here is more than 200 trillion times anything on the earth.

The core of a neutron star probably has the most extreme conditions in the entire modern universe. Here pairs of spin half neutrons become connected in a particular way to form what we call Cooper Pairs. These Cooper Pairs act as single spin 0 or spin 1 particles. Hence some of the fermions effectively become bosons. In the case of neutrons, they become a superfluid, which is a frictionless fluid that can sustain vortices with enormous amounts of energy. (15)Some physicists think that the dissipation of the vortices is seen by us glitches in the frequency in the flashes of pulsars. The rare Cooper pair protons on the other hand turn the core into a superconductor, which is probably an essential part of maintaining the neutrons star's enormous magnetic field.

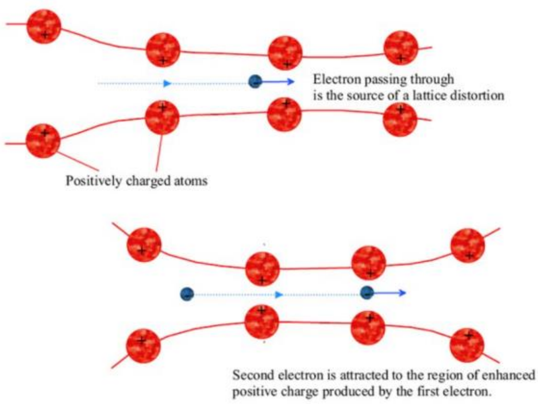

Figure 12: A static model of Cooper pair formation(Stefano et al)

6.1 What's right in the center?

Approaching the dead center of the neutron star the protons and neutrons start to lose structure and get compressed together. Now, this is all highly theoretical but it may be that at these extreme pressures and energies we find hyperon particles containing strange quarks. Another hypothesis is that they might not be bound into particles at all. The protons and neutrons may dissolve completely into a quark-gluon plasma. These plasmas have been seen in collider experiments but they only last for a fraction of a second.

7. Matter accretion

Matter accretion into the neutron star is accompanied by thermonuclear storms. As accretion continues the neutron star grows in mass. After a certain point (>3Msun) it will form an inescapable event horizon and collapse into a black hole.

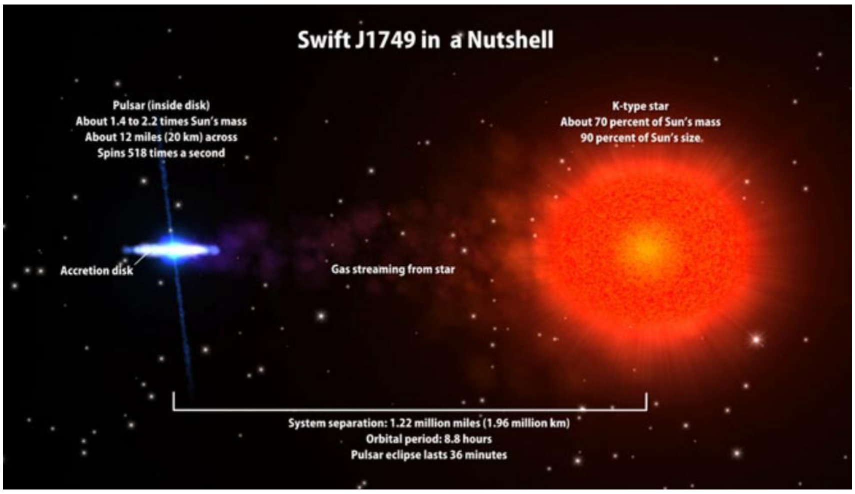

Figure 13: An illustration showing neutron star accreting matter(credits: NASA)

These are the brightest x-ray sources in the sky and were the first x-ray sources discovered. They have a wide range of properties (spectral and temporal) and show an almost bewildering array of behaviors. Their luminosities range over 6 orders of magnitude and are highly variable.(13)

NSs which accrete matter from their companion stars,

– either from the stellar winds or

– from an accretion disk that forms if the companion overflows its Roche lobe.

• The gravitational energy from the infalling matter provides the energy for the observed radiation and the accretion torques that dominate the spin evolution.

• Despite these common properties, accreting NSs display a wide variety of behaviors, depending on the NS magnetic field strength, the mass of the companion, and properties of the accretion.

8. Pulsars and observations from Earth

Just like a magnet, the magnetic field of a neutron star exists through its north pole wraps around the star, and enters it through the south pole. The neutron star thus has a magnetic axis which in most cases is not aligned with its axis of rotation. As the neutron star spins its magnetic field follows this rotation creating intense fluctuations which propagate at the speed of light. When an object is reasonably close the magnetic field of the neutron star traps the surrounding matter and forces it to stay near the star. Conversely, at a great distance, the magnetic field varies so quickly that it accelerates charged particles outwards. In this way, the neutron star produces extremely powerful beams of electromagnetic radiation that escape along its magnetic axis. (14)Like a cosmic lighthouse, these radiation beams sweep space periodically and emit a signal whose oscillation pulses metronomically. When the earth is in the way we observe a tiny bright spot that flickers in the sky. This is called a Pulsar.

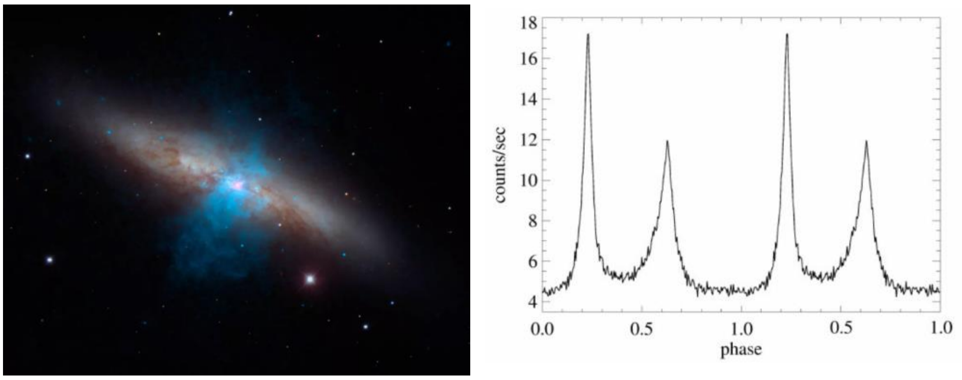

Figure 14: left :A pulsar (pink) can be seen at the center of the galaxy Messier 82 in this multi-wavelength portrait. The pulsar was discovered by NASA's NuSTAR which detected the pulsar's X-ray emission. (Image credit: NASA/JPL-Caltech) right: a sample observation data of pulsar

Since the 1960s Pulsar observations have been listed and classified according to their frequency of oscillation. The faster a neutron star spins on itself the faster the pulses we observe on earth.

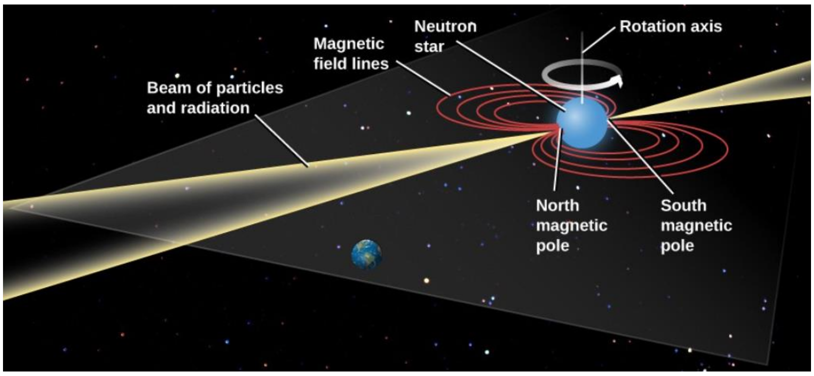

Figure 15: A cartoon diagram showing how a beam of pulsar sweeps through our earth(credit Tony Hewrett)

We can categorize different populations of Pulsars. Some spin very quickly at almost 1000 rotations per second. Most of these very fast pulsars occur in a binary system orbiting a star. They can accelerate to these extreme speeds by capturing matter from their companion.

Conversely, other Pulsars spin more slowly at a rate of a few revolutions per minute. The rotation of a neutron star is extremely stable. Its precession is comparable to that of our best atomic clocks. However, during its existence, the Neutron star slowly looses its energy, both magnetic and gravitational in the curvature of space-time. Gradually pulsars loose speed and end up performing only a few rotations per minute. During this slowing down process, the surface of the neutron star adjusts the centrifugal force which becomes weaker and takes a more spherical shape. Suddenly the surface falls a few micrometers in less than a millionth of a second. These phenomena have the effect of slightly accelerating the rotation of the star. Usually, the population of pulsars is classified in a PP diagram.

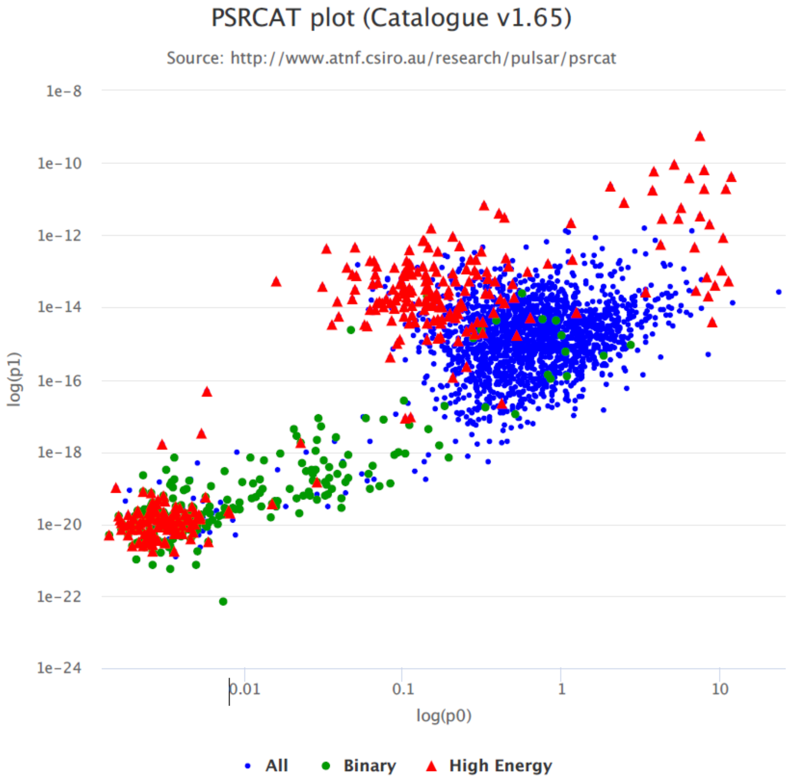

Figure 16: PP diagram of the ATNF pulsar catalog (credits: ATNF)

From earth, we observe all types of radiation. Most pulsars emit radio waves but others can emit more energetic Xrays because of their rotation and strong magnetic field. Some pulsars also emit gamma rays.

At this point, we know of nearly 3000 pulsars in our galaxy. Unfortunately, a vast majority of neutron stars remain unobservable from the earth. Most of them have very thin beams that don't sweep our sky. Our current telescopes can detect only the most active pulsars.

9. Magnetars

A magnetar (short for magnetic star) is a neutron star with a magnetic field that is extremely powerful. At ~10^{15} gauss, the magnetic field is a thousand trillion times stronger than the Earth's, and between 100 and 1,000 times stronger than that of a radio pulsar, making them the most magnetic objects known. It is not entirely clear what conditions cause a magnetar to be created instead of an ordinary neutron star or pulsar, but to achieve such strong magnetic fields, some theories suggest the neutron star must initially rotate between 100 and 1,000 times per second.

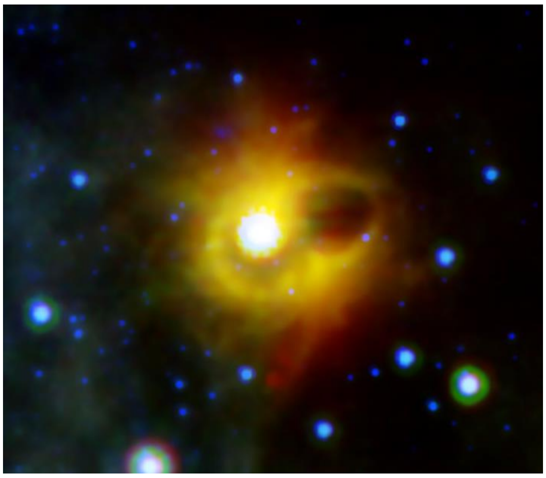

Figure 17 : Magnetar SGR 1900+14 (center of image) showing a surrounding ring of gas 7 light-years across in infrared light, as seen by the Spitzer Space Telescope. The magnetar itself is not visible at this wavelength but has been seen in X-ray light.

In 1987, the concept of a magnetar was initially introduced, and in 1992, it was effectively used to explain soft gamma repeaters (SGR). Few people took it seriously until 6 years later, when pulsations were detected and the spin-down rate of an SGR was measured, indicating that it was a neutron star with a magnetic field strength of $8*10^{14}$ gauss.

Since that time, both SGRs and anomalous X-ray pulsars have been explained successfully by the magnetar model, with the decay of the magnetic field powering the emission of X-rays and gamma rays.(15) However, it appears that magnetars are only X-ray bright for a short period since their pulse periods are clustered between 6 and 12 seconds. If they remained active for an extended period, we should also see magnetars with pulse periods of tens of seconds or longer.

10. Gravitational Wave Observations

Observation of gravitational waves is becoming common due to Advanced-LIGO VIRGO(upgraded version). While electromagnetic emissions provide important information about the astrophysical processes within, the prompt emission along with gravitational waves uniquely reveals the extreme matter and gravity during a merger.

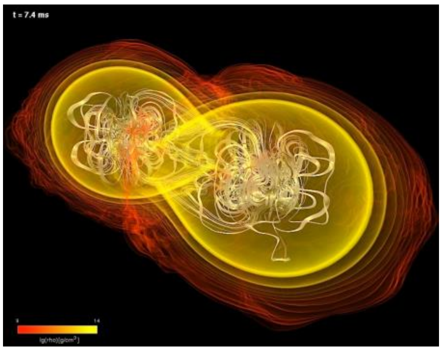

Figure 18: Binary Neutron star(credits: Albert Einstein Institute

Each binary pair creates a unique pattern of gravitational waves, but the mechanism of wave generation is the same across all three. It is called "inspiral". Inspiration occurs when two dense compact objects spin around each other over millions of years. They release gravitational waves as they orbit, which carry away some of the system's orbital energy. As a result, the objects circle closer and closer together over time. Moving closer, unfortunately, causes them to orbit each other faster, which causes them to generate stronger gravitational waves, which causes them to lose more orbital energy, inch closer, orbit faster, lose more energy, move closer, orbit faster... and so on.

The masses of the objects involved dictate how long they emit detectable gravitational waves. Heavy objects, such as black holes, move significantly faster through their final inspiral phase than 'lightweight' objects, such as neutron stars. This indicates that black-hole merger signals in LIGO are substantially shorter than neutron star merger signals, with significant discrepancies. The first pair of merging black holes observed by LIGO, for example, produced a signal that was only two-tenths of a second long. In comparison, the first neutron star merger observed by LIGO in August 2017 produced a signal that lasted more than 100 seconds in our equipment.

11. **Conclusion**

I have talked in detail about the structure of neutron stars and how they can be found. Pulsars, which we saw as a type of neutron allow us to probe into the theory of general relativity to its most extreme limits, help us understand the behavior of matter under such intense pressure and density. They provide us with cosmic clocks of extraordinary stability and precision. Their study also contains clues about the behavior of gravitational waves.

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