Griffin McAvoy

3/31/2020

AST-371-01

Dr. Ming Sun

Neutron Star Interiors at a Glance

Abstract

Neutron stars are the most compact objects in the universe except for black holes, and they are far better understood. Neutron stars (Baade & Zwicky, 1934) and their properties (Oppenheimer & Volkoff, 1937) were predicted in the 1930s, but were not discovered until 1967 (Tretkoff, 2006). Since then, detailed modeling, electromagnetic spectrum observation, and gravitational wave detection have allowed us to study the structure of these extreme objects and the exotic types of matter they contain. These methods have determined that neutrons stars are differentiated into inner and outer crusts and a core, possibly with inner and outer layers as well. The outer crust is composed of normal atomic nuclei surrounded by degenerate electrons and is further separated into numerous sublayers of different elemental composition (Chamel, 2020). The inner crust consists of the same type of matter as the outer crust, interspersed with degenerate neutrons in structures called nuclear pasta. Below the inner crust is an outer core composed entirely of degenerate neutrons (Yakovlev, 2015). There may also be an inner core within that, composed of quark-gluon plasma (Orsaria, 2019). While the characteristics of the inner core remain unknown, they are unlikely to remain that way in this era of multi-messenger astronomy. Since the simultaneous detection of a gamma-ray burst and gravitational waves from a neutron star merger in 2017, it has now become possible to correlate electromagnetic telescope observations with measurements from gravitational wave detectors (Abbott et al., 2017). This

new capability will greatly help astrophysicists narrow the constraints on the equation of state of neutron stars and thereby better understand the characteristics of their cores.

I. Introduction

The interior of a neutron star boasts of more intense pressures and densities than can be found in any environment outside of a black hole. Due to these extreme conditions, neutron stars are composed of exotic states of matter that are unencountered elsewhere. While it is currently impossible to directly observe these unusual states or simulate them in particle accelerators such as CERN's Large Hadron Collider, detailed mathematical modeling can be used to predict their characteristics. Furthermore, it may soon become possible to discern more details of neutron stars' inner workings by observing kilonovas (collisions between two neutron stars, or between a neutron star and a black hole) and pulsar behavior with gravitational-wave observatories like LIGO or VIRGO and advanced X-ray telescopes such as the Neutron star Interior Composition Explorer (NICER) currently aboard the International Space Station. This paper provides a summary of what is known and predicted about the mysterious interiors of these extreme objects, and what has recently or may soon be learned with the developing techniques of multi-messenger astronomy.

This paper is divided into several sections. Section II briefly details the history of neutron star astronomy as it pertains to the internal structure of those objects. Sections III and IV describe the outer and inner crusts of neutron stars, respectively. Section V covers neutron stars' cores. Section VI discusses the application of multi-messenger astronomy to the study of neutron stars.

II. History of Relevant Astrophysical Observations

Before discussing the most up-to-date knowledge of neutron stars' complex inner workings, I will provide some historical context. The existence of neutron stars was first proposed in 1934 by Frizt Zwicky and Walter Baade as a possible product of supernova explosions (Baade & Zwicky, 1934). Soon thereafter, physicists began mathematically modeling the characteristics of these still-theoretical objects (Oppenheimer & Volkoff, 1937). However, they were not actually discovered until 1967, when Jocelyn Bell Burnell and Antony Hewish detected the first pulsar (Tretkoff, 2006). The internal structure of neutron stars was accurately predicted mathematically at least as early as 1972 (Arponen, 1972). Expanded understanding of physics, better mathematical methods, and improved computer simulations have allowed astrophysicists to greatly refine those initial models of neutron star interiors over the years.

III. Outer Crust

Like a terrestrial planet, a neutron star is differentiated into distinct layers: an inner and outer crust and an inner and outer core. The outer crust is the only part of the star composed entirely of "normal" atomic matter. The nuclei collect into numerous layers of varying thickness and density, each composed solely of a specific variety of nucleus (Chamel, 2020). The sublayers are surrounded by a flowing sea of degenerate electrons, like that which exists in white dwarf stars (Chamel, 2020). The outer crust is very thin relative to the rest of the star and makes up only a small fraction of its mass (Yakovlev, 2015). It stretches from the surface of the neutron star to the "neutron drip point", the depth at which sheer pressure begins to overwhelm the strong force holding the nuclei together, causing the neutrons to “drip” out of the nuclei (Chamel, 2020).

SUBLAYERS OF THE OUTER CRUST		
Element	**Isotope**	**Thickness of Layer (fraction of drip depth)**
Iron	58	.0207
Nickel	62	.0778
Nickel	64	.0785
Nickel	66	.004
Krypton	86	.053
Selenium	84	.123
Germanium	82	.116
Zinc	80	.118
Nickel	78	.126
Ruthenium	126	.035
Molybdenum	124	.095
Zirconium	122	.046
Strontium	120	.087
Strontium	122	.018
Strontium	124	.002

Figure 1: Table showing the elemental and isotopic composition and thickness of each outer crust sublayer. Layer thicknesses are given as a fraction of drip depth because the drip depth and therefore the thicknesses of each atomic layer vary based on the mass of the neutron star in question. Note that all species have an even number of both protons and neutrons, as odd-numbered isotopes are not stable under these conditions. (Chamel, 2020).

IV. Inner Crust

Below the drip point, various structures composed of normal atomic matter float within a sea of degenerate neutrons, collectively comprising the inner crust. These structures are referred to as “nuclear pasta” due to their superficial resemblance to different types of noodles. The uppermost pasta layer is called the "gnocchi" layer because it forms into roughly spherical bubbles of degenerate neutrons within atomic matter (Starr, 2018). Below that is "spaghetti," where the neutrons collect into long, thin rods (Yakovlev, 2015). Beneath the spaghetti is a layer of "lasagna," so called because the atomic matter and degenerate neutrons coalesce into large, flat, alternating slabs (Yakovlev, 2015). Below the lasagna, these structures are inverted – there is an "anti-spaghetti" phase of atomic rods in a neutron sea, and finally a "Swiss cheese" phase of atomic bubbles within the neutron fluid (Yakovlev, 2015). The nuclear pasta and outer crust together form a layer approximately one kilometer thick, but the crust collectively makes up only about one percent of a neutron star's total mass. (Yakovlev, 2015).

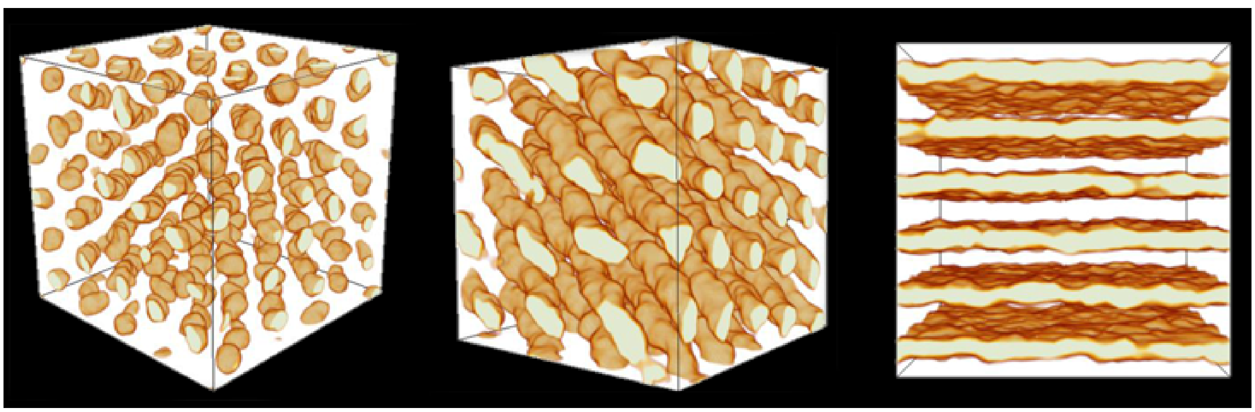
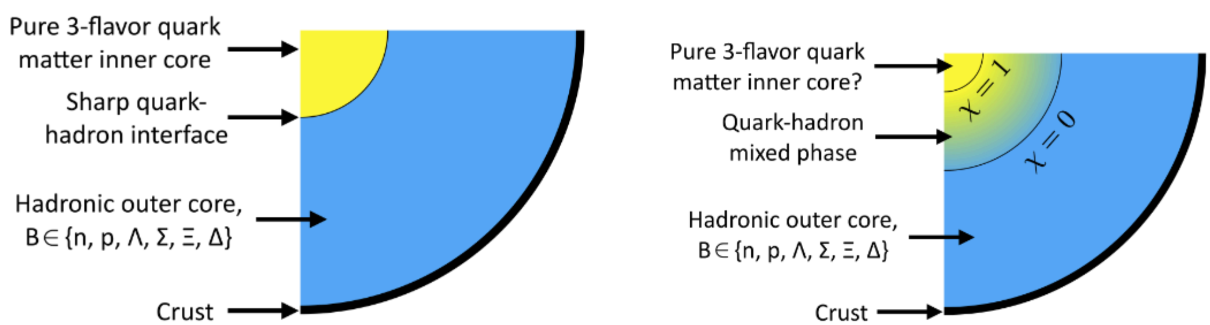


Figure 2: Computer-generated images showing the gnocchi, spaghetti, and lasagna phases of nuclear pasta. (Conover, 2018).

V. Core

Beneath the pasta is the thick outer core of superfluid degenerate neutrons, which makes up most of the star's mass (Yakovlev, 2015). However, at the very center of the star, pressure becomes so intense that quarks begin to drip out of neutrons, much as the neutrons themselves dripped out of atomic nuclei (Yakovlev, 2015). The free sub-nucleonic particles resulting from this process from a quark-gluon plasma (Orsaria, 2019). However, there is great uncertainty as to how much quark-gluon plasma is created and what structures it forms. Akmal et al. predicted in 1998 that little to no quark matter is present. Any that does exist, they claim, could only be present as small drops because their calculations found that a star with a pure quark core would be unstable (Akmal et al., 1998). However, Orsaria et al. (2019) more recently predicted that there is such a core. Depending on the surface tension between the two types of matter, the transition from degenerate neutrons to quark-gluon plasma could be an abrupt one or a gradual shift through another set of "pasta" structures. The usual estimate for the surface tension is no more than 30 mega-electronvolts per square femtometer; if this is really the case, the transition would be a sharp one as depicted in Figure 3(a). If, however, the surface tension exceeds about 70 mega-electronvolts per square femtometer (as some other estimates show), neutron stars would exhibit the transitional mixed phase as shown in figures 3(b) and 4 (Orsaria et al., 2019).



(a) Hypothetical NS cross section with a pure quark phase.

(b) Hypothetical NS cross section with a mixed phase.

Figure 3: Diagram depicting two possible cross-sections of a neutron star. Source: "Phase transitions in neutron stars and their links to gravitational waves" (Orsaria et al., 2019).

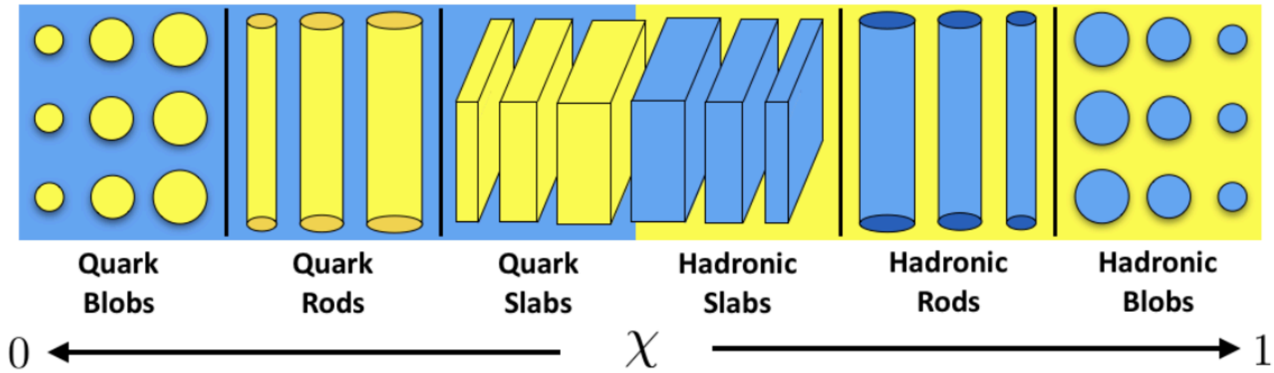


Figure 4: Simplified diagram depicting the hypothesized gradual transition from hadronic matter (degenerate neutrons) to quark matter. Note the similarity to nuclear pasta (Orsaria et al., 2019).

VI. Multi-Messenger Astronomy

The era of multi-messenger neutron star astronomy began when, in August of 2017, the Fermi Gamma-ray Burst Monitor detected a gamma ray burst (GRB) (Abbott et al., 2017). This event was notable because the Light Interferometer Gravitational-wave Observatory (LIGO) and its European counterpart Virgo detected a gravitational wave (dubbed GW170817) less than 10 minutes later (Abbott et al., 2017). The data from the two gravitational wave observatories indicated that the detected event had been a merger between two neutron stars (Abbott et al., 2017). The close timing of the gravitational wave detection and the GRB indicated that the latter had been produced by the same event (Abbott et al., 2017). In an unprecedented feat of international scientific collaboration, scientists around the world combed through mountains of telescope data from the entire electromagnetic spectrum to isolate the specific source of the GRB and the gravitational waves (Abbott et al., 2017). This stupendous effort was not in vain; the merger's location, an elliptical galaxy called NGC 4993, was determined before the day ended (Abbott et al., 2017).

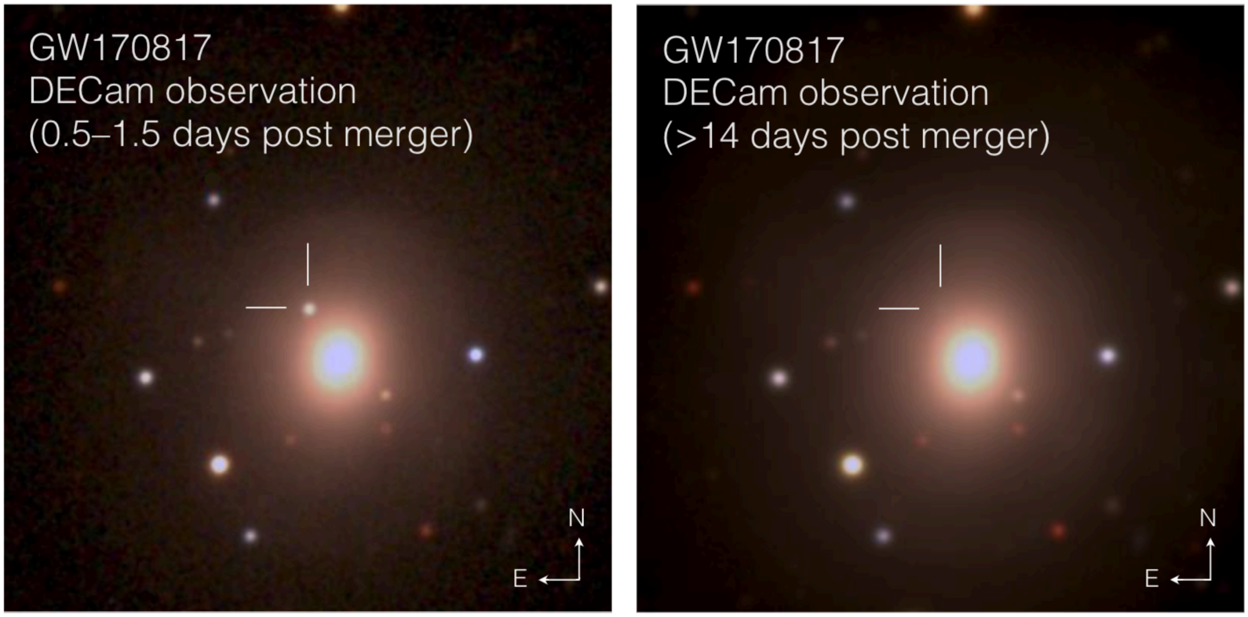


Figure 5: The optical flash emitted by the same neutron-star merger that produced GW170817 ("GW170817 - The first observation of gravitational-waves from a binary neutron star inspiral").

In the 2019 paper "Introduction to multi-messenger astronomy", Andrii Neronov said "The new field of multi-messenger astronomy aims at the study of astronomical sources using different types of "messenger" particles: photons, neutrinos, cosmic rays and gravitational waves." Beginning with GW170817, multi-messenger astronomy can now be applied to neutron stars (Abbott et al., 2017). This is a significant development; now that the results from electromagnetic and gravitational wave observations can be compared, it is possible to measure and describe the characteristics of neutron stars far more precisely.

In 2019, one study used NICER's observations of the neutron star PSRJ0030+0451 and LIGO/Virgo data from GW170817 to place constraints on neutron stars' equation of state (Raaijmakers et al., 2019). This equation of state describes the various states of matter within neutron stars and the transitions between them. If it could be sufficiently better defined, many of the uncertainties mentioned above would be resolved.

VII. Conclusions

Neutron stars are fascinating objects. The intense conditions within these stellar remnants, where gravity and the strong force collide, push the boundaries of what is physically possible, producing many varieties of unusual matter. Our ability to predict the characteristics of this bizarre matter is a testament to the power of our science, but the cores of neutron stars remain somewhat of a mystery. Now, however, multi-messenger astronomy has opened new avenues into the unexplored depths of neutron stars. As our understanding of these objects deepens, so will our knowledge of the fundamental laws and forces that govern the entire cosmos. Truly, this is an exciting era for astrophysics.

References

Abbott, B. P.; et al. (LIGO, Virgo and other collaborations) (October 2017). Multi-messenger Observations of a Binary Neutron Star Merger. *The Astrophysical Journal. 848*(2): doi:10.3847/2041-8213/aa91c9.

Akmal, A., Pandharipande, V. R., & Ravenhall, D. G. (1998). Equation of state of nucleon matter and neutron star structure. *Physical Review C*, *58*(3), 1804–1828. doi: 10.1103/PhysRevC.58.1804

Arponen, J. (1972). Internal structure of neutron stars. *Nuclear Physics A*, *191*(2), 257–282. doi: 10.1016/0375-9474(72)90515-5

Baade, W., & Zwicky, F. (1934). Remarks on Super-Novae and Cosmic Rays. *Physical Review*, *46*(1), 76–77. doi: 10.1103/PhysRev.46.76.2

Chamel, N. (2020). Analytical determination of the structure of the outer crust of a cold nonaccreted neutron star. *Physical Review C*, *101*(3). doi: 10.1103/PhysRevC.101.032801

Conover, E. (2018, September 14). From Science News: "Nuclear pasta in neutron stars may be the strongest material in the universe". Retrieved from https://sciencesprings.wordpress.com/2018/09/14/from-science-news-nuclear-pasta-in-neutron-stars-may-be-the-strongest-material-in-the-universe/

GW170817 - The first observation of gravitational-waves from a binary neutron star inspiral. (n.d.). Retrieved April 28, 2020, from https://www.ligo.org/detections/GW170817.php

Starr, M. (2018, September 17). Weird 'Nuclear Pasta' Could Be The Strongest Material in The Universe. Retrieved from https://www.sciencealert.com/nuclear-pasta-10-billion-times-stronger-than-steel-gravitational-wave-neutron-stars

Tretkoff, E., & Ouellette, J. (2006, February). This Month in Physics History. (A. Chodos, Ed.)*APS News*. Retrieved from https://www.aps.org/publications/apsnews/200602/upload/feb06.pdf

Neronov, A. (2019). Introduction to multi-messenger astronomy. *Journal of Physics: Conference Series*, *1263*(1). doi: 10.1088/1742-6596/1263/1/012001

Oppenheimer, J. R., & Volkoff, G. M. (1939). On Massive Neutron Cores. *Physical Review*, *55*(4), 374–381. doi: 10.1103/PhysRev.55.374

Orsaria, M. G., Malfatti, M. G., Mariani, M., Ranea-Sandoval, I. F., Garcia, F., Spinella, W. M., … Weber, F. (2019). Phase transitions in neutron stars and their links to gravitational waves . *Journal of Physics G: Nuclear and Particle Physics*, *46*(7). doi: 10.1088/1361-6471/ab1d81

Raaijmakers, G., Greif, S. K., Riley, T. E., Hinderer, T., Hebeler, K., Schwenk, A., … Ludlam, R. M. (2019). Constraining the dense matter equation of state with joint analysis of NICER and LIGO/Virgo measurements . *The Astrophysical Journal Letters*. Retrieved from https://arxiv.org/pdf/1912.11031.pdf

Yakovlev, D. G. (2015). Electron transport through nuclear pasta in magnetized neutron stars. *Monthly Notices of the Royal Astronomical Society*, *453*(1), 581–590. doi: 10.1093/mnras/stv1642