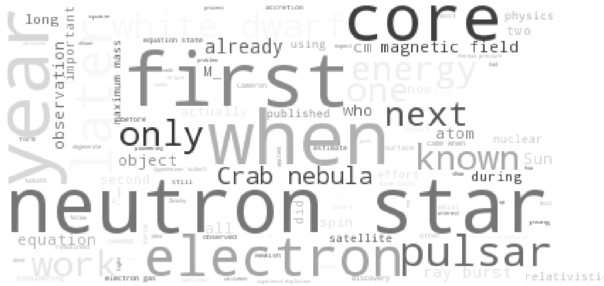

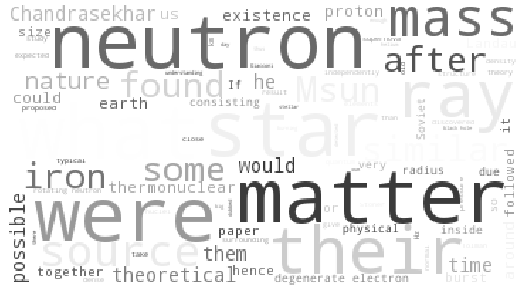

1 Introduction

Neutrons stars are curious objects encompassing many still unsolved problems of modern physics and astrophysics. Their unique nature makes them ideal laboratories for many of the most energetic phenomena in space. Born from the ashes of a supernova, they begin their life only when some other normal star fades away and dies in a spectacular supernova explosion.* From there on, they continue their life by slowly collecting the surrounding interstellar matter or by devouring an unlucky companion star floating next to them. It is not the impressive $\sim 10^{30}$ kilograms they weight but the mere $\sim 10\,\mathrm{km}$ in radius sphere that they encapsulate this material into that is then able to bend the spacetime itself. Such an impressive feat rewards them with a categorization into a special stellar group called *compact objects*. Along with white dwarfs and black holes, these strange compact objects have been under a scientific scrutiny for almost nine decades now. Still, some of the most fundamental questions remain: What are neutron stars made of? How big are they? How do we see them?

In the next few sections, we will discuss these peculiar objects habiting the Space around us in detail. First, a short history of their discovery is given, followed by simple physical arguments why we actually expect them to exists in a first place. This will hopefully help us in building some intuition of physics that are possible near and inside these stars.

1.1 Short history

1.1.1 From imagination into a reality

In 1908, Lev Landau was born in Baku, Azerbaijan. Landau turned out to become a brilliant Soviet scientist who already at an age of 14 matriculated from the Baku State University studying in both, Department of Physics and Mathematics, and the Department of Chemistry simultaneously. Soon after that he became disinterested in chemistry but continued to be fascinated by physics through his whole career. In 1931, at an age of 23, Landau published an exceptional paper where he speculated on the existence of stars containing matter on nuclear densities:†

> *...the density of matter becomes so great that atomic nuclei come in close contact, forming one gigantic nucleus.*

What made this paper exceptional was that it was done before the existence of neutrons were confirmed. For the contemporary science this meant a violation of quantum mechanics because during those times, atoms were thought to consist of protons and electrons only, and they certainly could not exists together in a same place inside such a hypothetical star. Nevertheless, it marked the first theoretical speculation on the existence of what we now know as neutron stars.

Landau needed not to wait for long. It was already next year in 1932, that James Chadwick confirmed that neutrons really were a fundamental part of our nuclear physics with his works dubbed as *Possible Existence*

*For the pedantic ones, we specify that a supernova is actually an implosion followed by a subsequent explosion.

† [1] L. D. Landau. *Phys. Z. Sowjetunion.* (1932).

of a Neutron[*] and a later follow-up of *Existence of a Neutron*[†]. His experimental findings then confirmed the theoretical predictions of his supervisor Ernest Rutherford made already in 1920[‡]. Later on, Chadwick was awarded the Nobel Prize in physics, in 1935, of his findings. Chadwick himself continued his career as part of the Manhattan project, as it was basically his groundbreaking work that inspired the U.S. government to begin a serious atomic bomb research.

Now that the existence of the neutron was confirmed, it did not take long for others, independent of Landau, to propose similar stars. One year after the neutron discovery, in December 1933 at the Meeting of the American Physical Society at Standford, Wilhelm Baade and Frank Zwicky made their famous propose that Supernovae should be considered as a new category of astronomical objects.[§] At the same time they also stated:

> *...we advance the view that a super-nova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density.*

Such a statements were, however, deemed as a work of imagination from a bunch of weird theorists. Zwicky, on the other hand, kept on insisting that neutron stars are really out there. More later on, A.G.W. Cameron, a former post-doc during the 1959−1969 at Caltech where Zwicky was also situated, recalls:

> *For years Fritz [Zwicky] had been pushing his ideas about neutron stars to anyone who would listen and had been universally ignored. I believe that the part of the problem was his personality, which implied strongly that people were idiots if they did not believe in neutron stars.* (Cameron, 1999)

Progress on the theoretical understanding of neutron stars was also tightly connected to understanding the interiors of white dwarfs. Unlike the mysterious nuclear forces related to neutrons, white dwarfs physics was more related to understanding the behavior of electrons. A breakthrough in this field came in 1925 when a young Paul Dirac formulated the quantum wave equations for the motion of the electrons[¶]. What soon followed, was a description of a pressure of degenerate electron gas by Ralph Fowler, Dirac's supervisor[‖]. Implications of this were severely against the previously known physics: Even in zero temperature, there would be a degeneracy pressure preventing matter from collapsing, due to the exclusion principle of quantum mechanics.

Using a simplified uniform density approximation, Edmund Stoner was then able to show that this implied a maximum mass limit for white dwarfs.[**] Thus, a surprising result was obtained: when the density of a white dwarf approaches infinity, the mass reaches a maximum value. It was later on realized by German-Estonian Wilhelm Anderson that the electrons in this problem must actually be treated relativistically[††], something omitted by Stoner. Anderson also tried to correct the crude mistake by deriving the equation of state of relativistic degenerate electron gas but ended up making severe mistakes. It was then Stoner who corrected his equations, based on the communications with Anderson, and re-derived his maximum mass limit. Regardless of Stoner's efforts, the maximum mass limit was later named Chandrasekhar's mass limit for its importance in astrophysics.

---

[*] [2] J. Chadwick. *Nature*. (1932).

[†] [3] J. Chadwick. *Proceedings of the Royal Society of London Series A*. (1932).

[‡] [4] E. Rutherford. *Proceedings of the Royal Society of London Series A*. (1920).

[§] [5] W. Baade and F. Zwicky. *Proceedings of the National Academy of Science*. (1934); [6] W. Baade and F. Zwicky. *Physical Review*. (1934).

[¶] [7] P. A. M. Dirac. *Proceedings of the Royal Society of London Series A*. (1925).

[‖] [8] R. H. Fowler. *MNRAS*. (1926).

[**] [9] E. C. Stoner. *Philos. Mag.* (1930).

[††] [10] W. Anderson. *Zeitschrift für Physik*. (1929).

This was to honor Subrahmanyan Chandrasekhar, a young prolific Indian physicist and astrophysicist who was working on the same topic after reading Fowler's paper on the degenerate electron gas. Unlike Stoner's limit computed using the uniform density approximation, Chandrasekhar realized that a polytropic density profile is a more physical, albeit mathematically more challenging formulation. 19 years old Chandrasekhar, already known for his mathematical skills, was still able to numerically integrate the equations by hand and obtained a similar limiting mass*. Later on, it has been, however, found that Chandrasekhar was not even the second person to derive the mass limit, but a third:† A soviet physicist Yakov Frenkel published a similar derivation, independently and unknowingly of the progress in the West, where he applied the relativistic degenerate electron gas results to white dwarfs, and concluded that an upper limit on the mass must exist‡. It was, however, due to the slow publishing pace in the Soviet journals, that his work never became available to his Western peers on time.

Nevertheless, a maximum mass for a white dwarf was laid out, and in the end after all the relevant physical inclusions, it turned out to be 1.44 $M_\odot$, or 1.44 times the mass of our Sun. What makes this limit important for us, is that a maximum mass for a white dwarf is just a minimum mass for a neutron star. An important connection first made by George Gamow in 1939§. Idea behind this is simple: If it is the degenerate electron gas pressure, quantum mechanical in nature, that keeps the white dwarfs from collapsing, what happens when the maximum mass is attained and even this pressure is note able to resist the forces of gravity? At a conference in Paris in 1939, Chandrasekhar then laid out the answer:

> *If the degenerate core attain sufficiently high densities, the protons and electrons will combine to form neutrons. This would cause a sudden diminution of pressure resulting in the collapse of the star to a neutron core.*

A neutron star should thus have a mass close to the Chandrasekhar limit, i.e. $M \sim 1.44\,M_\odot$, and consist of neutrons only. Exactly like proposed by Landau eight years ago without the knowledge of neutrons, or more later on by Baade and Zwicky when they presented their theory of supernovae!

It was before the second World War, that a solid basis for a theory of neutron stars was laid out. This was, however, just the beginning. Next question would be the critical one that we are still trying to find the answer to: If they exists, how big are they? The problem was that because of the extremely dense nature of these objects, the classical stellar equilibrium equations were not valid anymore, and because of this, it was not possible to estimate even the size of a neutron star. The problem was unwieldy because it was general relativistic in nature: The immense mass of the neutron star was bending the spacetime itself, and more compact it was, the more it could bend it. On the other hand, the more curved the spacetime was, the more the star would gain weight and more compact it would become.

It was already during the same year in 1939 as Gamow's remark, that a theoretical framework for studying this was published. This was done independently by Richard Tolman¶, and Robert Oppenheimer together with his student George Volkoff‖. Both papers were even submitted on the same day, 3rd of January, to Physical Review and were published on the same February issue. More importantly, they both described a hydrostatic equilibrium for a spherically symmetric object in general relativity, exactly what is needed to study neutron stars. Because of the utter importance, the solution is now known as Tolman-Oppenheimer-Volkoff equation. In addition, Oppenheimer and Volkoff applied their equation and numerically calculated a structure of a neutron star consisting of non-interacting strongly degenerate neutron gas. This marked the first try in characterizing neutron stars. Similar to white dwarfs, they also obtained an upper limit for the

* [11] S. Chandrasekhar. *MNRAS*. (1931).
† [12] D. G. Yakovlev. *Physics Uspekhi*. (1994).
‡ [13] J. Frenkel. *Zeitschrift für Physik*. (1928).
§ [14] G. Gamow. *Physical Review*. (1939).
¶ [15] R. C. Tolman. *Physical Review*. (1939).
‖ [16] J. R. Oppenheimer and G. M. Volkoff. *Physical Review*. (1939).

mass. As a disappointment for everybody, it was, however, calculated to be of around 0.7 $M_\odot$, i.e. less than the Chandrasekhar limit of 1.44 $M_\odot$ for white dwarfs, indicating that neutron stars could not exist in nature. It took almost two decades then to show that it was actually the assumption of no interaction between the neutrons that was causing this hiccup.

More over, it was not actually Tolman, or Oppenheimer and Volkoff who first discovered general relativistic hydrostatic equation. It was now Chandrasekhar's turn to avoid having an important result credited to him: Together with John Von Neumann, Chandrasekhar extended his work on white dwarfs to cover also neutron stars and in the process derived exactly the same equilibrium equation in 1934, i.e., five years before the groundbreaking publication of Tolman, Oppenheimer and Volkoff.* It is, however, worth mentioning that later on, in 1983, Chandrasekhar received a Noble prize in physics for his work on "theoretical studies of the physical processes of importance to the structure and evolution of the stars". So he certainly received at least some credit from his important work.

Around the same time, in 1937, Gamow and Landau also independently proposed that a accretion of matter onto a dense neutron star core could be the missing source of energy for stars. This increased the interest towards neutron stars and the field flourished on the 1930s. Soon it was, however, shown that stars are powered not by accretion but by thermonuclear reactions (as suggested in the 1920s by Eddington and others). The interest in neutron stars then faded away and the research focused on weaponizing the nuclear forces.

Next big breakthrough came almost 20 years later in the 1950s, when John Wheeler and his collaborators constructed the first realistic equation of state of dense matter†. For the outer layers, known as the crust, they applied a semi-empirical mass formula together with the equation of state of degenerate electrons. For the dense core, they assumed a mixture of three ideal Fermi gases composed of neutrons, protons, and electrons. This marked the first consistent formulation for the neutron star structure. It was followed by Cameron who applied the Skyrme equation of state for the high-density matter.‡ This had important implications, as he was then able to show that the nuclear forces stiffen the matter considerably in comparison to the non-interacting free neutrons. Similar to Tolman and Volkoff, he then went on and calculated the maximum possible mass of a neutron star and obtained approximately 2 $M_\odot$. This marked an important theoretical breakthrough as it implied that neutron stars can, after all, exists. A new wave of interest towards neutron stars was thus launched as everybody wanted to observe them.

1.1.2 Many observational faces of neutron stars

After Wheeler and Cameron laying the modern foundation for the neutron star structure studies, everybody was eager to find these strange objects from the night sky. It did not take long, when researchers realized that as neutron stars are born in the supernova explosions, we expect them to be hot. Most of the theoretical effort in the 60s was then focused on developing models for the cooling of neutron stars.§ It was the possible thermal radiation from this cooling that could then be used to detect them, as was first shown by Hong-Yee Chiu¶. First calculations predicted surface temperatures of $T \sim 10^6$ K for a neutron star of around 1000 years old. This had important implications for the observers as it meant that neutron stars would radiate mainly in the X-rays. Atmosphere of Earth, on the other hand, was impenetrable in the X-ray wavelengths. Luckily, 60s also marked the beginning of of a golden era for spaceborn observatories.

When X-rays did not reach the earth, humankind went to space to observe them. In the late 1950s and early 1960s it was the pioneering experiments of italian astrophysicist Riccardo Giacconi that opened this

* [17] G. Baym. 1982.

† [18] J. A. Wheeler. *ARA&A*. (1966).

‡ [19] A. G. Cameron. *ApJ*. (1959).

§ [20] R. C. Stabler. 1960; [21] H.-Y. Chiu. *Annals of Physics*. (1964); [22] D. C. Morton. *Nature*. (1964); [23] H.-Y. Chiu and E. E. Salpeter. *Physical Review Letters*. (1964); [24] J. N. Bahcall and R. A. Wolf. *Physical Review*. (1965); [25] J. N. Bahcall and R. A. Wolf. *ApJ*. (1965); [26] S. Tsuruta and A. G. W. Cameron. *Canadian Journal of Physics*. (1966).

¶ [21] H.-Y. Chiu. *Annals of Physics*. (1964).

new window to the Universe. Giacconi started first with rocket-borne experiments and later on continued by leading the development of the first orbiting X-ray satellite Uhuru, "*freedom*" in Swahili.[*] After the first X-ray satellite, Giacconi then continued with the Einstein Observatory, the first fully imaging X-ray satellite, and later with Chandra X-ray observatory. For all of his efforts, he received the Noble Prize in Physics in 2002 "for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources".

During the starting boom, several extra-terrestrial X-ray sources were discovered. Like is common in science, first discovery actually came by accident. A team led by Giacconi launched an Aerobee 150 rocket in June 1962 to the skies with a payload of highly sensitive soft X-ray detector meant to observe the X-rays from the moon. Due to a slight change (or a mistake) in the planned trajectory it ended up observing towards the constellation of Scorpius and caught a glimpse of what is now known as the first X-ray, Sco X−1. Little did they know that this was actually a first neutron star radiating to us. Five years later, in 1967 Iosif Shklovsky was first to propose that Scorpius X-1 is a neutron star[†], but his work attracted little to no attention.

First intended observations to find neutron stars were aimed towards the Crab nebula, a well-known candidate to hosting a neutron star. The Crab Nebula, already known from 1920s and 1930s to be a supernova remnant, is known to be exploded exactly in 4th of July, 1054.[‡] In the contemporary Chinese, Japanese, and Arab history writings, a "guest star" is described to appear in the constellation of Taurus, and to persist even in the day-sky for 23 consecutive days. Even after that, it remained visible in the night sky for two years. For astronomers, this was a clear sign of a nearby supernova going off.

But it was not only the spectacular supernova, but what was left behind that eluded astronomers. Already in 1942, our old friend Baade and Rudolf Minkowski correctly found that the center of the Crab nebula contained an unusual star.[§] In the following years, the mystery deepened when radio emission was also detected.[¶] This gathered a lot of interest from the theorists as they were trying to explain the origin of the energy powering the nebula. In 1953, Shklovsky was on the right track again, when he predicted that the emission is due to synchrotron radiation from relativistic electrons spiraling along magnetic field lines. Next piece of the puzzle came in 1964, when Lodewijk Woltjer, who did his PhD on the Crab nebula, argued based on a conservation of magnetic flux, that neutron stars should have a strong magnetic field, enough to produce this synchrotron radiation.[‖] Similar result was independently obtained in the East by Vitaly Ginzburg.[**]

Early X-ray telescopes of the time had a very poor angular resolution so imaging the Crab nebula to get an answer to the puzzle was hard. The first observation in 1964 by S. Bowyer et al. used a clever method of partial lunar occultation to cover unwanted parts of the sky with the Moon, and what followed was the first X-ray observation of the neutron star candidate everybody was waiting for.[††] It was, however, followed by a disappointment when a follow-up observation measured the source size as about 1 light-year in size (10^{13} km) in comparison to the 11 light-years for the whole nebula.[‡‡] The result was much larger than what was expected for a neutron star that should be of mere $\sim 10\,\mathrm{km}$ in radius. Ironically, what they did not know, was that this was just as expected: For young neutron stars like the one in the Crab nebula, a pulsar wind (consisting of charged particles similar to Solar wind) is expected. This wind will then create a surrounding shell, much bigger in size, around the neutron star called plerion, that is the source of the X-rays. Hence, the mystery remained even though Nikolai Kardashev in the East and Franco Pacini in the West, gave plausible

[*] [27] R. Giacconi *et al*. *Physical Review Letters*. (1962).

[†] [28] I. S. Shklovsky. *ApJ*. (1967).

[‡] [29] J. H. Oort. 1997; [30] K. Lundmark. *PASP*. (1921); [31] N. U. Mayall. *Leaflet of the Astronomical Society of the Pacific*. (1939); [32] D. A. Green and F. R. Stephenson. 2003.

[§] [33] W. Baade. *ApJ*. (1942); [34] R. Minkowski. *ApJ*. (1942).

[¶] [35] J. G. Bolton, G. J. Stanley, and O. B. Slee. *Nature*. (1949).

[‖] [36] L. Woltjer. *ApJ*. (1964).

[**] [37] V. L. Ginzburg. *Soviet Physics Doklady*. (1964).

[††] [38] S. Bowyer *et al*. *Nature*. (1964).

[‡‡] [39] S. Bowyer *et al*. *Science*. (1964).

pioneering explanations for the formation of the wind in 1964 and 1967, respectively.*

Despite all the efforts (and partly due to bad luck) no concrete observations supporting the existence of neutron stars still existed. This all changed in the July 1967, in the farmlands near Cambridge. There, a pasture was filled with primitive antenna consisting of wires hanging from stakes — a state-of-the-art radio antenna of those times. The idea was to use this newly build radio telescope to study interplanetary scintillation that could help in resolving quasars, another form of compact objects powered by black holes from extended sources in the sky. Among several other students who were working for Anthony Hewish, was a young post-doc Jocelyn Bell. In addition to the signal from the scintillation, she discovered a deviation on her chart-recorded papers: an extremely regular signal of 1.3373012 seconds caught Bell's attention. Originally this was dubbed (partially as a joke) as Little Green Men 1 (LGM-1). In reality, what they were seeing, and what Bell quickly realized, was a first pulsar, a rapidly rotating neutron star whose radio emission beam sometimes points towards us, like a distant lighthouse. More Little Green Man quickly followed and by the end of the year 1968, a dozens of LGMs were known. The finding was later published in the Nature 1968 by Hewish.†

Hewish's announcement was quickly followed by a more than 100 papers on pulsars, speculating the possible origin of the signal. Winning argument came from Timothy Gold who showed that pulsars are strongly magnetized rapidly rotating neutron stars.‡ However, one should not forget the similar seminal theoretical paper already in 1967, before the discovery, from Pacini.§ More proof came when our old friend Crab nebula was shown to host a pulsar rotating at a period of merely 33 milliseconds.¶ Anything but a neutron star would be destroyed by the centrifugal forces from such a rotation.

The finding of Bell and Hewish was sensational and marked the first detection of a neutron star, almost 40 years after the theoretical speculation by Landau. Later on, Hewish was awarded the Noble prize in Physics in 1974 ”for the discovery of pulsars”, a somewhat unfair recognition taken into account that it was Bell who found them in practice. Hence, despite all the efforts in X-ray astronomy, the concluding evidence finally came from the radio wavelengths.

One should not, however, feel sorry for the X-ray astronomers, as they got their fair share of neutron star-related revelations during the next decade. Important discoveries especially to study the nature of accretion, how matter infalls to a compact object, came from the first long-duration observations done with the dutch astronomy satellite ANS. As a direct competitor for the europian ANS, the U.S. funded Los Alamos nuclear research center was also in the game to observe X-rays from compact objects. Their Vela-satellites were send to space mostly to monitor the compliance to the 1963 Partial Test Ban Treaty of nuclear weapons but they were used for science, too. In 1975 the ANS satellite was commisioned to study possible black holes in the center of globular cluster but happened to stumble upon something completely different: A short, $\sim$ 60 second long X-ray flares were detected from a globular cluster NGC6624 by Grindlay and Heise.‖ The competing Los Alamos group found similar energetic bursts, but due to the poor angular resolution (to collect X-rays from the Earth was easy and hence no effort was put for a good spatial accuracy) they could not pin point the exact location of the sources.** Later on, Clark et al. went through the existing SAS-3 data from May 1975 and found a series of ten similar bursts from the same location, NGC6624.†† Even more retrospect, it turned out that these strange flares had been observed already in 1969 from Cen X-4‡‡ with another Vela-satellite and in 1971 with the Soviet Kosmos 428 X-ray detector§§. Their nature, however,

* [40] N. S. Kardashev. *AZh*. (1964); [41] F. Pacini. *Nature*. (1967).

† [42] A. Hewish *et al*. *Nature*. (1968).

‡ [43] T. Gold. *Nature*. (1968).

§ [41] F. Pacini. *Nature*. (1967).

¶ [44] J. M. Comella *et al*. *Nature*. (1969).

‖ [45] J. Grindlay *et al*. *ApJ*. (1976).

** [46] R. D. Belian, J. P. Conner, and W. D. Evans. *ApJ*. (1976).

†† [47] G. W. Clark *et al*. *ApJ*. (1976).

‡‡ [48] R. D. Belian, J. P. Conner, and W. D. Evans. *ApJ*. (1972).

§§ [49] O. P. Babushkina *et al*. *Soviet Astronomy Letters*. (1975).

remained elusive.

Pioneering theoretical work on thermonuclear instabilities on the surface layers of accreting neutron stars was initiated by Hansen and van Horn in 1975.* They constructed stationary burning shells to lay on top of neutron stars but in contrast found out that most of them were actually unstable. Unstable here might not give the full meaning to the physical issue though: Such a layer on top of neutron star burning uncontrollably meant a spectacular firework. Shortly after the Los Alamos results came in, an italian astrophysicist Laura Maraschi, while visiting MIT in February 1976 was able to connect the dots and speculated that these recently observed X-ray bursts were due to thermonuclear flashes on the surface of accreting neutron stars.† Similar conclusion was done by Woosley and Taam in their 1976 paper titled "Gamma-ray bursts from thermonuclear explosions on neutron stars". Observational evidence soon followed when van Parajids et al. and Thorstensen et al. were independently able to optically resolve the companions of two known bursting sources, Cen X-4‡ and Aql X-1§. Not only did these observations confirm that there is a companion star close by, but that it must be to a such a close distance of the neutron star that accretion, i.e., a constant flow of new fuel for the explosions, must exist.

All of the aforementioned discoveries were, however, nothing but a prelude to what was discovered on the years to follow. We will end this short historical review by listing some of the most important more modern findings. A big revelation came in 1979 when a very intense burst of gamma-rays was detected by two Soviet satellites Venera 11 and Venera 12.¶ Later dubbed as Soft Gamma Repeaters (SGRs), their energy source remained mysterious for decades. Theoretical breakthrough came in 1992 when Robert Duncan, Chistropher Thompson, and Bohdan Paczynski showed that the bursts could originate from a neutron star with a magnetic field 100 to 1000 times more powerful then what was previously known.‖ Today these neutron stars are more commonly known as magnetars, a subclass of young neutron stars where the initial magnetic field has been amplified by some delicate dynamo processes during the supernova explosion. Another surprise came in 1982, when a team lead by Backer changed on how we look at pulsars when they found, using the world's largest radiotelescope in Arecibo, a pulsar spinning 641 times per second.** This new neutron star was dubbed as a millisecond pulsar and unlike its predesessors, we now know that instead of slowly decreasing in spin, it belongs to a class of old pulsars that have been spun up by the accretion. In 2000, our understanding of the thermonuclear X-ray bursts was also changed when Cornelisse observed a very long, not minutes but hours long, burst from a neutron star normally exhibiting regular short bursts.†† These were then dubbed as superbursts, in contrast to the normal burst. The reason in the difference is, we think, because of the burning material: normal bursts use hydrogen and helium as their fuel but superbursts can devour a more rare carbon shell in a matter of hours if the conditions are just right.

1.2 From first principles to a neutrons star

1.2.1 Background: Sun and stars

Let us first see, what can we learn from neutron stars using simple estimates and conservation laws. Neutrons star are born from a death of a normal star. Most familiar such a star is our Sun, one Astronomical Unit or 1.496×10^{13} cm from us.‡‡ With a mass of $M_\odot = 1.99 \times 10^{33}$ g and radius of $R_\odot = 6.96 \times 10^{10}$ cm, our Sun gives us an idea of typical stellar size scales. Curiously, these numbers also means that the mean density of

Stellar orders of magnitude

* [50] C. J. Hansen and H. M. van Horn. *ApJ*. (1975).

† [51] L. Maraschi and A. Cavaliere. 1977; [52] W. H. G. Lewin, J. van Paradijs, and R. E. Taam. *SSRv*. (1993).

‡ [53] J. van Paradijs *et al*. *ApJ*. (1980).

§ [54] J. Thorstensen, P. Charles, and S. Bowyer. *ApJ*. (1978).

¶ [55] E. P. Mazets *et al*. *Nature*. (1979).

‖ [56] R. C. Duncan and C. Thompson. *ApJ*. (1992).

** [57] D. C. Backer *et al*. *Nature*. (1982).

†† [58] R. Cornelisse *et al*. *A&A*. (2000).

‡‡ Throughout this thesis we will typically present our quantities only up to some fixed precision instead of the full litany of numbers. We will also adopt the centimeter-gram-second (cgs) unit system instead of the (maybe) more common SI-system. Such a selection is sure to disappoint some, but try to endure.

the Sun is $\rho_\odot \approx 1.41\,\mathrm{g\,cm^{-3}}$, a mere $1.4\times$ the density of the water.

Like all stars, our Sun is held together by the inward pulling gravity. Gravity does not prefer any direction more than some other and so a spherical object is expected to form. In addition to the inward-facing force, an outward-facing force is needed to balance the system. For normal stars this force is originating from the thermal pressure.

We observe stars in the night sky because they shine on us. This radiation, and also the origin of the thermal pressure, is from the thermonuclear fusion burning inside the star. *Thermo* here refers to the temperature and heat, *nuclear* to the atomic nuclei, and *fusion* to a process where elements are fused together. During the thermonuclear fusion process, the star's core fuses light elements such as protons into heavier ones like helium. Mass of two protons is less than a mass of one helium atom. This mass difference between the start and the end results is then transferred into energy in accordance to the Einstein's famous $E = mc^2$ formula. A whole sequence of such fusion processes takes place inside the star where lighter elements are merged together to build more and more heavier elements. This energy release from the mass-to-energy conversion will then give the star a sufficient thermal pressure support to keep it from not collapsing under the relentless gravity.

The fusion of elements does not continue forever. In the beginning, two protons collide two form a helium. In the next stage, three helium nuclei collide to form a carbon, and so on, until iron is created. Production of iron marks the end of the possible fusion chain because fusion of two iron cores does not release energy anymore. On the opposite, it requires external energy source to take place.* This iron produced, will then sink to the center of star forming a dead core without any energy output.

Like all big furnaces, at some point the stars will run out of fuel to burn. What is then left behind is a inner core of iron with a subsequent onion-like layers of lighter and lighter elements. Crucial question to ask next is: What is supporting this iron core now that the thermal pressure from the fusion processes are lost? To answer this, we need to look inside the iron atom: Iron nucleus, consisting of 26 protons and 32 neutrons, and surrounded by 26 electrons, repulses its neighbors because of the negatively charged electron cloud around it does not want to get in touch with its neighbors flying next to it in the iron-atom lattice. † It is this antisocial avoidance of neighboring particles, originating from the electric charge repulsion, that will then give the internal support for the iron core not to collapse under its own gravitational pull. If enough iron is build up during the lifetime of the star so that even this repulsion force is not enough, we can continue our thought experiment and ask, again, what will follow? This was the question that led the scientists like Chandrasekhar to the realization of degenerate matter and white dwarf stars in the 1920s.

1.2.2 White dwarfs and quantum mechanics

The answer originates from the elusive quantum mechanics. When the atoms inside the matter are packed close enough to each other, we need to apply wave-like characteristics for them, instead of the classical point-like thinking. Because of their smaller mass, the electrons orbiting the nuclei enter the realm of quantum mechanics first, in comparison to the heavier protons and neutrons in the atomic core. A freely moving electron confined into a small enough space because of the surrounding neighbors will start to attain only some fixed values of momenta. In physics we speak about quantization of energy levels. The reason is similar to a vibrating string of a guitar: a string fixed from both ends can only vibrate on some specific wave modes that are set by its length. Additional complication for the electrons is set by the Pauli exclusion principle that forbids more than one electron to occupy a same wave mode or a quantum state inside the

*This opens up another possibility of creating energy by splitting heavy elements, an inverse process to what is described here. Such a process is called fission and is familiarly taken advantage of in the Earthly nuclear power plants.

†More precise consideration shows that nickel ($^{56}_{28}$Ni) is actually thermodynamically more favored in the core because of the lack of neutrons needed to synthesize iron-58 ($^{58}_{26}$Fe). Underlying idea presented here, however, remains the same.

same region.* This gives rise to a degeneracy pressure as electrons fill their quantum states from the lowest to the highest, and can, hence, not be packed any more closely. A star held together by this degeneracy pressure of its electrons is known as a white dwarf. From this setup it only takes a short step into realizing the existence of neutron stars, because we can, again, push forward and ask what next?†

1.2.3 Neutron stars at last

What if at some point even these quantum effects of the electrons are not enough to support the star? One does not need to worry because after the lightweight electrons have given all they can, it is the heavy neutrons that slowly start to enter the quantum mechanical realm. In practice, the matter will turn into a one big team of neutrons because when the positive (+) central proton and the surrounding negative (−) electron come in contact, a neutral neutron is created.‡ The degeneracy pressure of such a neutron porridge is multiple orders of magnitude larger than what the electrons can offer yielding an ultimate solution to the pressure support problem.

Let us consider the consequences of this thought play. More detailed calculations show that the resulting iron-core sitting at the center of the star is weighting at a maximum of around $\sim M_{\odot}$.§ Hence, there are $M_{\mathrm{core}}/m_{\mathrm{atom}} \sim M_{\odot}/m_{\mathrm{p}} \approx 1.99\times10^{33}\,\mathrm{g}/1.67\times10^{-24}\,\mathrm{g} \sim 10^{57}$ atoms trapped inside the core. ¶ Here we are already considering not iron atoms but pure hydrogen atoms only to simplify the presentation. Working backwards from these numbers, we can estimate the size of the compressed core. Using a typical radius for the nuclei of $r_{\mathrm{n}} \approx 1.25\times10^{-13}\,\mathrm{cm}$, we would expect these particles to form an object of around $R \sim (10^{57})^{\frac{1}{3}} \times 1.25\times10^{-13}\,\mathrm{cm} \sim 10^{6}\,\mathrm{cm}$. Hence, we have ended up in a star consisting of only neutrons, with a size of $\sim 10\,\mathrm{km}$ and mass of $\sim 1\,M_{\odot}$, a neutron star!

By considering simple order-of-magnitude estimates we have now ended up characterizing the dimensions of a typical neutron star. A canonical neutron star is often taken to have $R = 10\,\mathrm{km}$ and $M = 1.4\,M_{\odot}$, so let us also adopt those numbers for the following considerations. Such dimensions give us an impressive mean density of $\rho \sim 7\times10^{14}\,\mathrm{g\,cm^{-3}}$. In comparison, for a typical nucleon (such as a neutron or a proton) we had $m_p \approx m_n \approx 1.67\times10^{-24}\,\mathrm{g}$ and $r_n \approx 1.25\times10^{-13}\,\mathrm{cm}$, yielding us a nuclear density of $\rho_{\mathrm{n}} \approx 2\times10^{14}\,\mathrm{g\,cm^{-3}}$. Not surprisingly, the densities are of similar magnitude. However, when comparing to our every-day matter, the difference is huge, almost 14 orders of magnitude: A cubic centimeter of water weights 1 g whereas a same volume of neutron star matter would weight 100 000 000 000 000 g or 100 million metric tons. Density

Matter compressed to such a small volume has an extreme impact even on the surrounding spacetime. Let us try to estimate, again, the order-of-magnitude of these effects by considering the escape velocity — a velocity needed to escape the local gravitational pull of an object. For us, on top of Earth, it turns out to be $v_{\oplus} = \sqrt{2GM_{\oplus}/R_{\oplus}} = 1.12\times10^{6}\,\mathrm{cm\,s^{-1}}$, for $M_{\oplus} = 5.97\times10^{27}\,\mathrm{g}$ and $R_{\oplus} = 6.37\times10^{8}\,\mathrm{cm}$. Similarly, for the Sun it is $v_{\odot} = 6.18\times10^{7}\,\mathrm{cm\,s^{-1}}$, or 0.002× the speed of light. On the other hand, for a neutron star we obtain $v_{\mathrm{NS}} = 1.93\times10^{10}\,\mathrm{cm\,s^{-1}}$, which is already about half of the speed of light! Hence, relativistic effects become crucial to take into account when considering neutron stars as one can not even escape from the surface of the star without velocities close to that of the light. Escape velocity

Let us next think about the possible spins rates that a neutron star can have. For our Sun, it takes 25.5 days or about one month to revolve around itself, corresponding to a spin rate of 4.5×10^{-7} Hz. When compressed Spin

*Explain Pauli repulsion for a layman

†The reader is reassured that the chain of thermal pressure → charge repulsion → electron degeneracy will next come to a halt as the final neutron degeneracy is really the final possible supporting force in Nature. Maybe excluding the quark matter, tough…

‡In reality the beta decay formula is $e^- + p = n + \nu_e$, where the additional electron neutrino is needed to preserve the quark color neutrality.

§This is quite reasonably sounding assumption taken into account that the stars that explode are of around $\sim 10\,M_{\odot}$ and we certainly do not expect everything to fall into the core.

¶The mass of the atom, $m_{\mathrm{atom}} = m_{\mathrm{p}} + m_{\mathrm{e}}$, is approximated (to an excellent accuracy) by just considering the central nuclei alone as the electron mass $m_{\mathrm{e}} \approx 9.11\times10^{-28}\,\mathrm{g}$ is negligible in comparison to the proton mass.

to a dimensions that of a neutron star the radius changes by a factor of $R_\odot / R_{\mathrm{NS}} \approx 6.96 \times 10^{10}\,\mathrm{cm}/10^6\,\mathrm{cm} \sim 7 \times 10^4$. It is important to notice that when a rotating object collapses, it preserves it's angular momentum not the spin rate. Similar to an ice-figure skater pulling her arms inwards while spinning, we observe an increase in the spin in order to preserve the angular momentum. As the rotational inertia increases as a square from the distance from the axis, our Sun, when compressed to a neutron star, would obtain a spin of $4.5 \times 10^{-7}\,\mathrm{Hz} \times (7 \times 10^4)^2 \sim 2 \times 10^3\,\mathrm{Hz}$. In reality, the young proto neutron star quickly slows down after its birth, and we are left with spins of around 10^2 to 10^3 Hz, still about one revolution per 1 to 10 milliseconds.

B-field

A final characteristic observable, we can try and estimate is the magnetic field. Here we can follow a similar chain of reasoning as with the spin and start from typical values such as those of our Sun. For the Sun, the slow rotation gives rise to a dynamo process that produces a magnetic field of around $B_\odot \approx 1\,\mathrm{G}$.* When considering magnetic field, it is the magnetic flux through the surface that conserves, hence we expect the field to scale also as a square of the radius. Using the same compression ratio of 7×10^4 for the radii, we then obtain $B_{\mathrm{NS}} \approx 1 \times (7 \times 10^4)^2\,\mathrm{G} \sim 10^{10}\,\mathrm{G}$. Comparing this to the strongest non-destructive magnet on Earth of 10^6 G, we start to grasp the level of energetics that the neutron stars have to offer: even their original non-amplified magnetic field is $\times 10\,000$ stronger. In some cases, a dynamo effect originating from the rotation of the star can amplify this field even further and we are left with ultra-strong fields of $B \sim 10^{15}$ G.

It fair to conclude that neutron stars are dominating the physical record tables in almost all of their aspects. They are *super*dense, *super*fast rotators, sources of *super*strong magnetic fields, and *super*rich in the range of physics involved. In short: they are *super*stars of physics!†

1.3 Connection to this thesis

In this thesis we study many aspects of the neutron stars ranging from their astrophysical environments to the nuclear physical interiors. In the end, our main goal is to use this plethora of information to better constrain the behavior of the ultra-dense matter inside the core.

*A typical refrigerator magnet is about 50× stronger with a magnetic field of 50 G.

†This is (jokingly) called the Pines theorem as everything is *super*- when considering neutron stars, as postulated by David Pines in a talk given at the conference on Neutron Stars: Theory and Observation (The NATO Advanced Study Institute, Crete, Greece, September 3–14, 1990).

2 Bibliography

[1] L. D. Landau. *Phys. Z. Sowjetunion*. 1, pp. 285–288. (1932). (See p. 1)
"On the theory of stars".

[2] J. Chadwick. *Nature*. 129, p. 312. (1932). (See p. 2)
"Possible Existence of a Neutron"
DOI: 10.1038/129312a0.

[3] J. Chadwick. *Proceedings of the Royal Society of London Series A*. 136, pp. 692–708. (1932). (See p. 2)
"The Existence of a Neutron"
DOI: 10.1098/rspa.1932.0112.

[4] E. Rutherford. *Proceedings of the Royal Society of London Series A*. 97, pp. 374–400. (1920). (See p. 2)
"Bakerian Lecture. Nuclear Constitution of Atoms"
DOI: 10.1098/rspa.1920.0040.

[5] W. Baade and F. Zwicky. *Proceedings of the National Academy of Science*. 20, pp. 259–263. (1934). (See p. 2)
"Cosmic Rays from Super-novae"
DOI: 10.1073/pnas.20.5.259.

[6] W. Baade and F. Zwicky. *Physical Review*. 45, p. 138. (1934). (See p. 2)
"Supernovae and cosmic rays"
DOI: 10.1103/PhysRev.46.76.2.

[7] P. A. M. Dirac. *Proceedings of the Royal Society of London Series A*. 109, pp. 642–653. (1925). (See p. 2)
"The Fundamental Equations of Quantum Mechanics"
DOI: 10.1098/rspa.1925.0150.

[8] R. H. Fowler. *MNRAS*. 87, pp. 114–122. (1926). (See p. 2)
"On dense matter"
DOI: 10.1093/mnras/87.2.114.

[9] E. C. Stoner. *Philos. Mag.* 9, p. 944. (1930). (See p. 2)
"The equilibrium of dense stars".

[10] W. Anderson. *Zeitschrift für Physik*. 56. 11, pp. 851–856. (1929). (See p. 2)
"Über die Grenzdichte der Materie und der Energie"
URL: http://dx.doi.org/10.1007/BF01340146.

[11] S. Chandrasekhar. *MNRAS*. 91, pp. 456–466. (1931). (See p. 3)
"The highly collapsed configurations of a stellar mass"
DOI: 10.1093/mnras/91.5.456.

[12] D. G. Yakovlev. *Physics Uspekhi*. 37, pp. 609–612. (1994). (See p. 3)
"FROM THE HISTORY OF PHYSICS: The article by Ya I Frenkel' on 'binding forces' and the theory of white dwarfs"
DOI: 10.1070/PU1994v037n06ABEH000031.

[13] J. Frenkel. *Zeitschrift für Physik*. 47. 11, pp. 819–834. (1928). (See p. 3)
"Zur wellenmechanischen Theorie der metallischen Leitfähigkeit"
URL: http://dx.doi.org/10.1007/BF01328642.

[14] G. Gamow. *Physical Review*. 55, pp. 718–725. (1939). (See p. 3)
"Physical Possibilities of Stellar Evolution"
DOI: 10.1103/PhysRev.55.718.

[15] R. C. Tolman. *Physical Review*. 55, pp. 364–373. (1939). (See p. 3)
"Static Solutions of Einstein's Field Equations for Spheres of Fluid"
DOI: 10.1103/PhysRev.55.364.

[16] J. R. Oppenheimer and G. M. Volkoff. *Physical Review*. 55, pp. 374–381. (1939). (See p. 3)
"On Massive Neutron Cores"
DOI: 10.1103/PhysRev.55.374.

[17] G. Baym. "Neutron stars: the first fifty years". *The Neutron and its Applications, 1982*. Ed. by P. Schofield. 1982, pp. 45–50 (see p. 4).

[18] J. A. Wheeler. *ARA&A*. 4, p. 393. (1966). (See p. 4)
"Superdense Stars"
DOI: 10.1146/annurev.aa.04.090166.002141.

[19] A. G. Cameron. *ApJ*. 130, p. 884. (1959). (See p. 4)
"Neutron Star Models."
DOI: 10.1086/146780.

[20] R. C. Stabler. "Energy Loss Mechanisms from Very Dense Stars." PhD thesis. CORNELL UNIVERSITY., 1960 (see p. 4).

[21] H.-Y. Chiu. *Annals of Physics*. 26, pp. 364–410. (1964). (See p. 4)
"Supernovae, neutrinos, and neutron stars"
DOI: 10.1016/0003-4916(64)90256-8.

[22] D. C. Morton. *Nature*. 201, pp. 1308–1309. (1964). (See p. 4)
"Neutron Stars as X-ray Sources"
DOI: 10.1038/2011308a0.

[23] H.-Y. Chiu and E. E. Salpeter. *Physical Review Letters*. 12, pp. 413–415. (1964). (See p. 4)
"Surface X-Ray Emission from Neutron Stars"
DOI: 10.1103/PhysRevLett.12.413.

[24] J. N. Bahcall and R. A. Wolf. *Physical Review*. 140, pp. 1452–1466. (1965). (See p. 4)
"Neutron Stars. II. Neutrino-Cooling and Observability"
DOI: 10.1103/PhysRev.140.B1452.

[25] J. N. Bahcall and R. A. Wolf. *ApJ*. 142, pp. 1254–1256. (1965). (See p. 4)
"An Observational Test of Theories of Neutron-Star Cooling."
DOI: 10.1086/148395.

[26] S. Tsuruta and A. G. W. Cameron. *Canadian Journal of Physics*. 44, p. 1863. (1966). (See p. 4)
"Cooling and detectability of neutron stars"
DOI: 10.1139/p66-156.

[27] R. Giacconi, H. Gursky, F. R. Paolini, and B. B. Rossi. *Physical Review Letters*. 9, pp. 439–443. (1962). (See p. 5)
"Evidence for x Rays From Sources Outside the Solar System"
DOI: 10.1103/PhysRevLett.9.439.

[28] I. S. Shklovsky. *ApJ*. 148, p. L1. (1967). (See p. 5)
"On the Nature of the Source of X-Ray Emission of SCO XR-1."
DOI: 10.1086/180001.

[29] J. K. Katgert-Merkelijn, ed. *The letters and papers of Jan Hendrik Oort as archived in the University Library. Leiden*. Vol. 213. Astrophysics and Space Science Library. 1997. DOI: 10.1007/978-94-011-5764-3 (see p. 5).

[30] K. Lundmark. *PASP*. 33, p. 225. (1921). (See p. 5)
"Suspected New Stars Recorded in Old Chronicles and Among Recent Meridian Observations"
DOI: 10.1086/123101.

[31] N. U. Mayall. *Leaflet of the Astronomical Society of the Pacific*. 3, p. 145. (1939). (See p. 5)
"The Crab Nebula, a Probable Supernova".

[32] D. A. Green and F. R. Stephenson. "Historical Supernovae". *Supernovae and Gamma-Ray Bursters*. Ed. by K. Weiler. Vol. 598. Lecture Notes in Physics, Berlin Springer Verlag. 2003, pp. 7–19. DOI: 10.1007/3-540-45863-8_2 (see p. 5).

[33] W. Baade. *ApJ*. 96, p. 188. (1942). (See p. 5)
"The Crab Nebula."
DOI: 10.1086/144446.

[34] R. Minkowski. *ApJ*. 96, p. 199. (1942). (See p. 5)
"The Crab Nebula."
DOI: 10.1086/144447.

[35] J. G. Bolton, G. J. Stanley, and O. B. Slee. *Nature*. 164, pp. 101–102. (1949). (See p. 5)
"Positions of Three Discrete Sources of Galactic Radio-Frequency Radiation"
DOI: 10.1038/164101b0.

[36] L. Woltjer. *ApJ*. 140, pp. 1309–1313. (1964). (See p. 5)
"X-Rays and Type I Supernova Remnants."
DOI: 10.1086/148028.

[37] V. L. Ginzburg. *Soviet Physics Doklady*. 9, p. 329. (1964). (See p. 5)
"The Magnetic Fields of Collapsing Masses and the Nature of Superstars".

[38] S. Bowyer, E. T. Byram, T. A. Chubb, and H. Friedman. *Nature*. 201, pp. 1307–1308. (1964). (See p. 5)
"X-ray Sources in the Galaxy"
DOI: 10.1038/2011307a0.

[39] S. Bowyer, E. T. Byram, T. A. Chubb, and H. Friedman. *Science*. 146, pp. 912–917. (1964). (See p. 5)
"Lunar Occultation of X-ray Emission from the Crab Nebula"
DOI: 10.1126/science.146.3646.912.

[40] N. S. Kardashev. *AZh*. 41, p. 807. (1964). (See p. 6)
"Magnetic Collapse and the Nature of Intense Sources of Cosmic Radio-Frequency Emission".

[41] F. Pacini. *Nature*. 216, pp. 567–568. (1967). (See p. 6)
"Energy Emission from a Neutron Star"
DOI: 10.1038/216567a0.

[42] A. Hewish, S. J. Bell, J. D. H. Pilkington, P. F. Scott, and R. A. Collins. *Nature*. 217, pp. 709–713. (1968). (See p. 6)
"Observation of a Rapidly Pulsating Radio Source"
DOI: 10.1038/217709a0.

[43] T. Gold. *Nature*. 218, pp. 731–732. (1968). (See p. 6)
"Rotating Neutron Stars as the Origin of the Pulsating Radio Sources"
DOI: 10.1038/218731a0.

[44] J. M. Comella, H. D. Craft, R. V. E. Lovelace, and J. M. Sutton. *Nature*. 221, pp. 453–454. (1969). (See p. 6)
"Crab Nebula Pulsar NP 0532"
DOI: 10.1038/221453a0.

[45] J. Grindlay, H. Gursky, H. Schnopper, D. R. Parsignault, J. Heise, A. C. Brinkman, and J. Schrijver. *ApJ*. 205, pp. L127–L130. (1976). (See p. 6)
"Discovery of intense X-ray bursts from the globular cluster NGC 6624"
DOI: 10.1086/182105.

[46] R. D. Belian, J. P. Conner, and W. D. Evans. *ApJ*. 206, pp. L135–L138. (1976). (See p. 6)
"The discovery of X-ray bursts from a region in the constellation Norma"
DOI: 10.1086/182151.

[47] G. W. Clark, J. G. Jernigan, H. Bradt, C. Canizares, W. H. G. Lewin, F. K. Li, W. Mayer, J. McClintock, and H. Schnopper. *ApJ*. 207, pp. L105–L108. (1976). (See p. 6)
"Recurrent brief X-ray bursts from the globular cluster NGC 6624"
DOI: 10.1086/182190.

[48] R. D. Belian, J. P. Conner, and W. D. Evans. *ApJ*. 171, p. L87. (1972). (See p. 6)
"A Probable Precursor to the X-Ray Nova Centaurus XR-4"
DOI: 10.1086/180874.

[49] O. P. Babushkina, M. I. Kudriavtsev, A. S. Melioranskii, I. A. Savenko, B. I. Iushkov, and L. S. Bratoliubova-Tsulukidze. *Soviet Astronomy Letters*. 1, pp. 32–34. (1975). (See p. 6)
"Hard X-ray bursts in June 1971".

[50] C. J. Hansen and H. M. van Horn. *ApJ*. 195, pp. 735–741. (1975). (See p. 7)
"Steady-state nuclear fusion in accreting neutron-star envelopes"
DOI: 10.1086/153375.

[51] L. Maraschi and A. Cavaliere. "X-ray bursts of nuclear origin?" *X-ray Binaries and Compact Objects*. Ed. by K. A. van der Hucht. 1977, pp. 127–128 (see p. 7).

[52] W. H. G. Lewin, J. van Paradijs, and R. E. Taam. *SSRv*. 62, pp. 223–389. (1993). (See p. 7)
"X-Ray Bursts"
DOI: 10.1007/BF00196124.

[53] J. van Paradijs, F. Verbunt, T. van der Linden, H. Pedersen, and W. Wamsteker. *ApJ*. 241, pp. L161–L164. (1980). (See p. 7)
"Spectroscopic observations of the optical counterpart of Centaurus X-4"
DOI: 10.1086/183382.

[54] J. Thorstensen, P. Charles, and S. Bowyer. *ApJ*. 220, pp. L131–L134. (1978). (See p. 7)
"The optical counterpart of Aquila X-1 /3U 1908+00/"
DOI: 10.1086/182651.

[55] E. P. Mazets, S. V. Golentskii, V. N. Ilinskii, R. L. Aptekar, and I. A. Guryan. *Nature*. 282, pp. 587–589. (1979). (See p. 7)
"Observations of a flaring X-ray pulsar in Dorado"
DOI: 10.1038/282587a0.

[56] R. C. Duncan and C. Thompson. *ApJ*. 392, pp. L9–L13. (1992). (See p. 7)
"Formation of very strongly magnetized neutron stars - Implications for gamma-ray bursts"
DOI: 10.1086/186413.

[57] D. C. Backer, S. R. Kulkarni, C. Heiles, M. M. Davis, and W. M. Goss. *Nature*. 300, pp. 615–618. (1982). (See p. 7)
"A millisecond pulsar"
DOI: 10.1038/300615a0.

[58] R. Cornelisse, J. Heise, E. Kuulkers, F. Verbunt, and J. J. M. in't Zand. *A&A*. 357, pp. L21–L24. (2000). (See p. 7)
"The longest thermonuclear X-ray burst ever observed?. A BeppoSAX Wide Field Camera observation of 4U 1735-44".