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Introduction

This chapter begins with an detailed summary of the work, written without technical terminology. Section 1.1 is intended for non-specialists, introducing the necessary background and presenting the main results of this thesis work. Scientific research should be shared and made accessible to the general public. Astronomy and astrophysics have the chance to naturally attract people of all ages, mostly with stunning images and mind-blowing facts. Section 1.1 does not attempt to convince the reader of the usefulness of this research, but rather attemps to explain this work in a comprehensible way, to be able to reach as many as possible. The summary does not contain any reference to previous publications, nor any acronyms that would hinder the reading. It is also provided in French for francophone readers (Appendix A).

After the non-technical summary, a section presents a short historical overview of dense matter and neutron stars over the last 100 years, since the theoretical prediction of the neutron. This historical review serves as an introduction to the section that follows it, where this thesis work is motivated in a more general context. Finally, a short section presents each of the chapters.

1.1 A Summary for Non-Specialists

This research consists, in a certain way, in performing autopsies of dead stars. What is inside? What type of matter composes their core? These are two questions to which astrophysics and nuclear physicists do not have a clear answer. Unlike a medical investigator who can look directly inside a corpse, it is impossible to directly look inside stars, dead or not. There are however indirect observational methods that are briefly described. But before that, it is important to explain what is called a dead star, and to motivate the reason behind these autopsies.

A star is "dying" when it runs out of the material fueling the nuclear reactions happening in its core during its lifetime. When this happens, the delicate balance between the inward force of gravity and the outward pressure of nuclear burning is broken. The fate of a dying star then depends on its initial mass:

- A low-mass star, like our Sun, will eject most of its outer layers in a colourful nebula and leave behind an object called white dwarf, a dead star without nuclear reactions. These are dense slowly cooling objects with about half the mass of the Sun compressed in a sphere about the size of the Earth. That corresponds to densities about 1 million times that of water[1].

- A star with a higher mass (more than eight times the mass of our Sun) dies in a radically different, more dramatic manner by exploding into a supernova. During the supernova explosion, the core of the progenitor star gets compressed to incredible densities, due to gravity. What is left after the supernova depends again on the initial mass of the progenitor star. The supernova explosions of the most massive stars lead to the formations of black holes; these mysterious compact objects that attract everything, even light, around them without any chance to ever escape. But if the dying star is not massive enough to form a black hole (but still above eight times the mass of our Sun), the remnant of a supernova explosion is a neutron star, the objects of interest in this thesis.

These objects are composed of the densest form of matter than we know. Anything denser, i.e., more compact, than a neutron star would collapse to a black hole, from which it is impossible to obtain any direct observational information.

[1] A teaspoon of white dwarf would have a mass of 5000 kg.

Figure 1.1 – This illustration compares the size of a neutron star with the size of a city, such as Montréal. Source: *NASA*'s Goddard Space Flight Center.

In that sense, neutron stars are more interesting than black holes, since they actually have an observable surface allowing astrophysicists to investigate many of their properties. Nonetheless, they are mysterious objects. Extreme densities have been mentioned above: try to imagine – if it is even possible – the mass of the Sun[2] compacted into a sphere roughly the size of Montréal (Figure 1.1). A teaspoon of neutron star matter would have a mass of about three billions metric tons. This is because the atoms have been compressed so much that all the empty space inside atoms (and there is a lot of it at normal densities) has been replaced by the nuclei of other atoms. A simple analogy would be to completely fill up the interplanetary space in our Solar System with many planets. No laboratory on the Earth is anywhere close to reproducing matter with such densities. In fact, neutron stars are the only place in the Universe where this type of matter exists. Therefore, observing neutron stars is the only way to understand how such dense matter can exist. This quest aims at finding one of the missing pieces in the grand scheme of matter.

[2] Our Sun has a mass of 2×10^{30} kg, that is 2,000,000,000,000,000,000,000,000,000,000 kg, or 2 billions of billions of billions of metric tons!

In the absence of experimental data from laboratories, nuclear physicist are proposing a plethora of theoretical models to describe the behaviour of ultra-dense matter, i.e., how the pressure of matter changes when the density increases. Without means to test those experimentally, neutron stars provides the laboratories needed. There are several ways to probe the interior of neutron stars and discriminate between the multiple nuclear physics theories. The most common method is to measure the radii and/or the masses of neutron stars. Indeed, each of the proposed theories corresponds to very specific mass-radius relations for neutron stars. Therefore, measuring the masses and radii of neutron stars allows us to tell whether a theory appropriately describes ultra-dense matter or not.

The method used in this thesis consists in measuring the radius of neutron stars. This is basically done by measuring how hot and bright the surfaces of neutron stars are. A model of a neutron star surface can then help us convert the brightness into the actual radius of the neutron star. However, this method requires knowing the distance to the object observed. This is a frequent issue in astronomy. Without knowing the distances to astronomical objects, it is difficult to measure most of their properties. It is like looking at a light source (without any other point of reference) and trying to estimate how bright it is. Is it a dim and nearby light, or is it a bright and distant light? To answer this question, our brain interprets the surroundings to deduce the distance or the brightness. This is the same in astronomy where researchers need independent distance measurements in order to determine the brightness of objects.

Back to neutron star radius measurements: in this thesis, neutron stars inside clusters of stars are considered. Astronomers have developed independent techniques to measure the distances to star clusters. Therefore, neutron stars inside clusters have well measured distances, and therefore intrinsic brightnesses, compared to the other neutron stars for which we do not know the distance, for example, those wandering in our Galaxy. With those well known brightnesses, we deduce the radii of the neutron stars we observe.

However, there is another complication. For this radius-measurement method to work properly, we need to observe neutron stars with a quiet behaviour. Most neutron stars that could be use for radius measurements are in very active binary systems, with dramatic explosions on their surface, making the measurement of the radius difficult. Neutron stars often have a bright disk of matter revolving around them which dominates the brightness and therefore complicates the observation and the radius measurement. To avoid this problem, we can only use inactive, or *quiescent* neutron stars for which the emission we see is well understood and comes exclusively from the surface. There are only a few of these systems with known distances, i.e., inside the star clusters of our Galaxy.

From these few sources, we measured the radius of neutron stars to be between 7 km and 11 km (the size of a large city). This turns out to be smaller than expected from most of the theoretical models proposed by nuclear physics. The range of uncertainties of our result is still large and therefore there is still a lot of work to be done to obtain better measurements. But if such small values of the radius were to be confirmed, it might require revisiting the theory of ultra-dense matter. There are several ways to reduce the uncertainties in our radius measurement. For example, the distances to the clusters hosting the neutron stars we use are not perfectly known, and this lack of certainty of the distance measurements reflects on the radius measurement.

Overall, a lot more work remains to be done in the quest to understand ultra-dense matter, but this thesis work has made an important step toward it.

1.2 Historical Background

The historical background provided here first presents the physical and astrophysical knowledge related to neutron stars before their discovery. It is then followed by a section describing the first observations of neutron stars.