From models of the core and crust of neutron stars to observations of pulsars and X-ray sources

Neutron stars (NSs) are born in the supernova explosion that marks the end of the life of massive stars with a mass around 10 to 30 times the one of the Sun: $M_\odot \simeq 10^{30}$ kg. With a mass $M \simeq 1 - 2\,M_\odot$ for a radius $R \sim 10$ kilometers only, they are one of the densest form of matter in our Universe and General Relativity has to be used to describe their properties and dynamics. All NSs rotate from every few seconds to hundred of times per second around their spin axis. So far about 2500 NSs have been observed with radio, infrared, optical, UV, X-ray, and gamma-ray telescopes. The mass of approximately 60 of them has also been determined. NSs owe their existence and stability against gravity to the nuclear forces acting between the particles found in their interior. They are a unique "cosmic laboratory" to study nuclear physics and gravity under most extreme conditions that can not be reproduced on Earth. The properties of the matter inside NSs and the composition of their interior are still poorly known. Thus astrophysicists and nuclear physicists have developed many models for the nuclear force and consequently NS properties.

A NS can be divided into two main regions. The outer part, the crust, is made of neutron-rich atomic nuclei and a gaz of electrons and, at high density, neutrons. At the bottom of the crust, the nuclei disappear marking to the transition to the core, composed of neutrons and protons in addition to electrons and muons, all forming a gas. Some models even predict that exotic particles like hyperons or quarks can be found at the center of massive NSs. Hyperons are composed of three quarks like the neutron and the proton, but while these two particles are only made of quarks up and down, hyperons contain at least one strange quark.

The objective of the research project is to build models of NS interior that describe both the core and the crust using the same model for the nuclear force. The latter will be adjusted to reproduce properties of nuclei and nuclear matter that are measured in laboratory. Models of interior with and without hyperons will be computed. Then simulations of non-rotating and rotating NSs in General Relativity will be performed to calculate various NS properties like their mass, radius, maximum spin frequency, . . . In addition the evolution of the temperature inside NSs as they age will be modeled. The project will be carried out in collaboration with an international group of astrophysicists and nuclear physicists and consists in adapting and updating various previously employed numerical codes.

The results of the simulations will be confronted to NS observations which provide measurements of the mass and radius, the temperature at the surface, . . . of various NSs. These quantities can be determined by the current X-ray and radio telescopes and also with the new and future generation of instruments like NICER, FAST, SKA, and Athena. In addition the models of NS interior will be made available to the scientific community so that they can be used to explain the gravitational wave signal emitted by NSs and potentially observable by the LIGO and Virgo detectors. The comparison of the models with all these observational data together with the results of nuclear experiments in laboratory will enable us to rule out some models of NS interior thus helping understand better the properties of NS matter and of the nuclear force.