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Report on the thesis of Ms. Lami SULEIMAN

The thesis of Ms. Lami Suleiman addresses the topic of neutron stars, from three main approaches, one on the equation of state, another one on the crust/core description, and a last one on the cooling of the stars. Therefore, it is a very large amount of work that is presented in single thesis, as confirmed by the length of the manuscript (about 240 pages).

The first chapter is devoted to introducing neutron stars, both from the historical, modelization aspects, as well as from related experimental aspects. Although very short, this chapter is well-written and synthetic, hence useful.

The first main chapter of the thesis deals with the equation of state (EoS) in neutron stars. It first provides an accurate, up-to-date and historical introduction on EoS used in the modelization of neutron stars. Links are also made with observational programs, such as the ones dealing with gravitational waves. The main point of this study, which lead to 2 publications in refereed journals, is to study the impact of considering different EoS for the core and the crust of the neutron star (non-unified models). This includes the most recent constraints, with a large variety: tidal deformability, mass, radius, or moment of inertia of the star.

The comparison between unified and non-unified models, on these macroscopic quantities of the neutron stars, shows that non-unified model can bring misleading conclusions, in particular due to the choice of the matching density between the core and the crust. This information is valuable, especially in the view of the next generation telescopes, which will provide accurate constraints.

The next part of this chapter is devoted to study the role of non-unified approaches in the so-called quasi-universal relations, which empirically relate several macroscopic quantities of the neutron star. Here, the impact of non-unified EoS on the precision of the fit of these quasi-universal relations is analysed. Some bias is found in this fit, when a non-unified equation is used.

The last part of the chapter, deals with the polytropic EoS fitting of more microscopic EoS. This approach is used by the community to have a convenient analytical parametrization of more elaborated EoS. Here again, it is shown that considering non-unified equations of state, introduces non-negligible errors, on the polarizability, radius or moment of inertia. A revision of this method is proposed, based on a selected set of unified EoS. The results show an improvement in the description of the macroscopic quantities of the neutron stars.

This first main chapter therefore provide a useful analysis, and practical ways to improve the use of EoS, by quantifying the errors generated by the use of non-unified approaches, and proposing enhanced methods.

The second main chapter of the thesis is devoted to the study of the compression of the crust. Several aspects are treated. The first one is the impact of considering partially accreted crust instead of fully accreted ones, which remains an approximation. This more general approach is much more demanding, because it requires to consider the compression of the catalyzed (i.e. original) outer crust, in addition to the accreted material. To do so, the outer crust is divided in shells, which will be compressed by the accreted material. This will trigger exothermic reactions, from electron captures. It is found that most of the shells deep in the crust release less energy per nucleon than the one close to the surface. Moreover, the heat contribution from the compression of the catalyzed crust is found to be non-negligible, giving sound foundations to the present approach. Various other effects are then studied, such as the role of reaching the neutron drip line, on the number of reactions. Then, the thermal and transport properties of the original catalyzed crust are studied.

In the second main part of this chapter, the impact of the electron capture rate is included, which can change the kinetics of the processes under study. The electron capture rates are extracted from nuclear data sheets, considering the states of the parent and daughter nuclei, starting from 56Fe, in the case of the fully accreted crust. On that purpose, it is necessary to consider a model of equation of state for 2 nuclei, involving the parent nuclei of a given electron capture, and the daughter one of the next electron capture (hence the grand-daughter one). Several interesting results are obtained, such as the determination of the so-called layer of electron capture, i.e. the spatial region where the fraction of parent nuclei has not vanished yet. It is found that the heat release of the first few shells of the outer crust are impacted by the electron capture rates. Finally, the full continuity equation is solved, allowing to calculate the fraction of parent Fe nuclei, as a function of pressure and time. This study is useful and provide a contribution to the missing part of heating observed from the thermal relaxation of accreting neutron stars.

The last chapter of the thesis deals with the improvement of the description of the modified urca process, involved in the cooling of neutron stars. For this purpose, a microscopic formalism is used, based on quantum field theory. Several aspects are studied, involving the role of the momentum transfer and the full momentum dependence of the rate of this process. The inclusion of temperature effects is also considered, which is relevant in the case of hot young cooling neutron stars. The leptonic sector is first discussed with a Fermi distribution as a function of the energy of the weak boson involved. However, the numerical results are focused on the hadronic sector of the modified urca process. The polarization function is shown to correspond to a heavy integral of dimension eight, which is numerically calculated using the

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Monte Carlo method. It should be noted that a couple of approximations are removed in this calculation, such as the simple intermediary propagator. The intermediary nucleons are dressed using a constant parameter. An interesting regime, for moderate temperature (few MeV) and density (one-tenth of the nuclear saturation density), is predicted, where the modified urca process could be of the same order as the direct one, close and above the direct urca threshold. This is unusual because in other regimes, the Direct urca process is known to be a fast one, compared to the modified Urca process which is a slow one. This result may have an impact on the description of the cooling of the neutron star.

The thesis is very well written, and very clear, despite its large length. Useful appendixes on the modified urca part, including on the Matsubara formalism, are given. Moreover, the amount of work on various aspects of neutron stars (equation of state, crust, cooling) is very important and of very high quality. In each of these fields, the candidate shows her broad knowledge, and also brings some significant contributions to the international community. Most advanced approaches are developed, and useful results are obtained. Clear paths of continuation for future works are also identified. Both the quality and the quantity of work exposed in this manuscript make it an outstanding piece of original research.

Summing up, I consider the doctoral thesis of Lami Suleiman to be a valuable contribution and to meet the criteria prescribed by the law for a doctoral dissertation. Therefore, I request that this dissertation be admitted to a public defense.

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