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Review report on Lami Suleima's PhD thesis

entitled "Dense matter properties and neutron star modelling"

The doctoral thesis of Lami Suleiman, prepared under the supervision of prof. Julian Leszek Zdunik and dr Micaela Oertel deals with the general problem of the influence of the properties of ultra-dense matter inside neutron stars on their global parameters. Mgr Suleiman undertook the study of three different important aspects of dense matter modeling, crucial for understanding the properties of these the most dense stable objects in the Universe. One of primary goals of the dissertation is to contribute to the challenge of extracting information about the structure, composition of neutron stars and physical processes occurring in their interior or on their surface from multi-messenger observations. Thus, the research conducted by Lami Suleiman is consequently important not only for astrophysics but also for fundamental physics.

Suleiman's doctoral thesis is written in English. It consists of an abstract in Polish, English and French, a list of symbols used in the dissertation, a list of physical constants, a table of contents, six chapters, three appendices, 13 tables, 82 figures and a very extensive bibliography of almost 300 entries. It has 243 pages. A Chapter 1 is the outline of the manuscript. Chapter 2 contains a very basic and short introductory information regarding neutron star physics. The main original results of Suleiman's work are presented in Chapters 3, 4 and 5 while a relatively short Chapter 6 summarizes the thesis. The presentation of the original research of the author occupies more than 75 % of the entire dissertation. The content of chapters 3 and 4 was also a base for three peer reviewed papers with Lami Suleiman as the first author. Two papers entitled *"Influence of the crust on the neutron star macrophysical quantities and universal relations"* and *"Polytropic fits of modern and unified equations of state"* were published in Physical Review C and one paper *"Partially accreted crusts of neutron stars"* in Astronomy and Astrophysics.

The presentation of original results starts in Chapter 3 devoted to the role of the non-unified equations of state (EOS) of dense matter (where a crust and a core of a neutron star are not computed with the same nuclear model) on the modeling of various macrophysical parameters of neutron stars. The author calculated the relative error on the gravitational mass, the radius, the moment of inertia and the tidal deformability with respect to unified constructions for broad ranges of non-unified EOS. She found that this error was not negligible taking into account current and future multi-messenger observations. This can also affect conclusions of numerical simulations in which non-unified EOS is used e.g. magneto-hydrodynamical and finite temperature simulations or gravitational waves searches. This is an important result. In section 3.5 mgr Suleiman presents results on analytical representations of fifty two modern, unified equations of state of neutron stars. It

was shown that the global parameters of neutron stars calculated using tabulated and fitted EOS are in very good agreement. The parameters for the piecewise polytropic fits, calculated by her, are publicly available now. She intends to implement a unified EOS for numerical tools of the Ligo-Virgo-Kagra (LVK) collaboration in the near future. This would be an important and useful contribution to the search for gravitational wave signals in the data in the next LVK observing campaign.

In Chapter 4 the PhD candidate studies partially accreted crusts of neutron stars under assumption that a small amounts of matter is accreted. This is a new and more realistic approach to the commonly used the fully accreted crust approximation. It was motivated by observations of some X-ray transients in which the crust has not been completely replaced by accreted material. The author of the doctoral thesis considers a two-part crust made of the original, compressed crust and of the accreted material.

She studied the evolution of the structure, the composition, and the heat sources of a neutron star crust. Several interesting and innovative results were obtained.

In particular it was shown that

-properties of fully accreted and hybrid crusts are different and influence the cooling and transport properties,

-the amount of heat associated with the compression of the original crust and in the accreted part of the hybrid crust are on the same order of magnitude,

-the outer crust layers of electron captures have significant (20%) impact on heat release.

Chapter 5 concentrates on the very important subject of cooling of neutron stars. This chapter is more technical than chapters 3 and 4 so several formulas are presented in appendices A, B and C at the end of the dissertation what was a good decision. The author focused on cooling via the Modified Urca neutrino emission. She starts with clear introduction on the Direct and the Modified Urca processes and gave a brief overview of the status of Modified Urca neutrino emissivity calculations (section 5.1). In section 5.2 the derivation for the neutrino emissivity of the Modified Urca process at finite temperature was given. The main results of the Monte-Carlo integration for the hadronic part of Modified Urca are presented at the end of the chapter. Results are presented for various ranges of density, temperature and electron fraction. It was shown that the Modified Urca process might be relevant for finite temperature neutron stars i.e a binary merger remnant or a new born proto-neutron star. This is an interesting and important result.

Summarizing, the description of the results is coherent and clear. All assumptions are well described and discussed. The work is nicely written in a very good English. It is well prepared from the graphic side. The flaws of the dissertation (below) are few and do not concern the fundamental issues.

Flaws

- the introduction is sketchy and in my opinion the author should provide a broader and more detailed overview of the properties of neutron stars from both an observational and theoretical point of view.
- the bibliography is arranged in order of appearance in the text, however the references are not numbered. This makes it very difficult to identify concrete papers that the author refers to, taking into account that the literature is very extensive. Another solution would be to arrange the bibliography in the alphabetical order.

In conclusion, the Lami Suleiman's doctoral thesis contains many interesting, innovative and useful scientific results, the development of which required a great deal of experience, inquisitiveness, meticulousness and an enormous amount of work. The dissertation shows that mgr Suleiman is a fully formed, independent young scientist with a very good background in both theoretical knowledge and the interpretation of observational data. She has a very good understanding of dense matter properties and neutron stars astrophysics. Results obtained by Lami Suleiman open a large field for future scientific projects.

Summing up, I consider the doctoral thesis *"Dense matter properties and neutron star modelling"* of Lami Suleiman to be a valuable contribution to physics and astrophysics of neutron stars 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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