# Review of the PhD dissertation "Neutrino Radiation-Hydrodynamics Simulations: Predicting Observable Signatures of a First-Order QCD Phase Transition in Compact Star Astrophysics"

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The PhD dissertation of Ms. Noshad Khosravi Largani, entitled "Neutrino Radiation-Hydrodynamics Simulations: Predicting Observable Signatures of a First-Order QCD Phase Transition in Compact Star Astrophysics", presents the results of a comprehensive and thorough analysis of the complex and very current problem of the core-collapse supernova explosion, particularly the results of simulations with the first-order QCD phase transition. The obtained outcomes contribute significantly to our understanding of this problem.
The Thesis is written in English. The Thesis consists of the abstract with its Polish version, the list of the author's publications: peer-reviewed articles relevant for this dissertation (3 items), other peer-reviewed articles (3 items), the list of presentations: presentations at national and international conferences and workshops (12 items), presentations at national and international schools (9 items). The author then lists her contributions to the thesis, the acknowledgments, and the contents. Next, there are lists of figures (53 items) and tables (18 items). The main body comprises seven chapters and a very extensive bibliography (384 items). The thesis is well written, in a style expected for research presentations, and, what should be emphasized, it keeps the reader interested. The author has demonstrated a broad knowledge and understanding of the research field. I am impressed by the number of publications the author has become acquainted with while performing this research.
Due to the significant and original contribution to the field of study, as well as a unique interpretation of the obtained results demonstrating a deep understanding of the research topics, I recommend this PhD dissertation for distinction.

A proper understanding of the supernova phenomenon has attracted much attention. Growing observational possibilities, including, among others, the results of gravitational wave observations and the development of numerical methods, not only create opportunities for the development of increasingly advanced theoretical models, but also provide opportunities for the verification of the obtained results. It should be noted that, due to the complexity of the issues discussed, there is a significant diversity in the presentation of the problems analyzed in the Thesis. This, in turn, confirms the author's extensive knowledge of these topics. Neutrinos play an essential role in massive star evolution, especially in their collapsing cores. The description of the core-collapse supernova phenomenon and the post-bound evolution demand the accurate treatment of neutrino transport and neutrino-matter interactions, which in turn require the usage of the Boltzmann transport equation. In the Thesis, the general relativistic neutrino radiation hydrodynamics simulations in spherical symmetry have been applied to obtain reliable results concerning the supernova explosion and to determine how neutrinos affect not only the explosion's dynamics but also the position of the shock formation and the evolution of a proto-neutron star. The presented results were obtained utilizing the code Agile-Boltztran, which solves the Boltzmann transport equation for the neutrino distribution functions. The hydrodynamic equations must be supplemented by equations of state that reproduce the physical conditions characterizing a supernova explosion event. The simulations of core-collapse supernovae with the first-order phase transition were based on the hadron-quark hybrid matter equations of state. Hadronic models include RMF models with density-dependent nucleon-meson couplings, RMF models with various nonlinear self- and mixed-meson interactions, and non-relativistic semifenomenological mean-field models. Extensions of these models cover finite-temperature cases and, in the BHB$\Lambda\phi$ EoS, the inclusion of the $\Lambda$ hyperon and the $\phi$ meson. Selected hadronic models have been used to model the RDF quark matter phase transition. The author showed that the results of numerical simulations depend on the applied equation of state and the selected stellar progenitor model. The latter factor turned out to be critical in the course of the post-bounce evolution and also in the appearance of the hadron-quark phase transition. An important factor characterizing the post-bounce evolution scenarios obtained from the numerical simulations of the core-collapse supernova is the mass accretion phase. In spherical symmetry, after the proto-neutron star has reached its maximum stable mass, further mass accretion onto the central proto-neutron star leads to the formation of a black hole. Another scenario becomes possible when the proto-neutron star model allows a quark core to exist inside it. After reaching the phase of pure quark matter, the collapse stops, and a second hydrodynamic shock wave is generated. According to the results obtained in the Thesis, the received explosion models are characterized by the second neutrino burst dominated by electron antineutrinos. As the author shows, the second neutrino burst can be used to analyze not only the dynamics of the explosion but also the details of the proton-neutron star hadron-quark matter properties. This idea seems very promising as far as supernovae observations are concerned. They open additional prospects for finding constraints on the dense neutron star matter.

Another result obtained by the author concerns the universal relations for rapidly rotating neutron stars. These concern the relations between the maximum mass of a rotating and non-rotating star and between their corresponding radii. In both cases, the quantities corresponding to the rotating configurations are increased compared to the non-rotating ones by factors of the order of 1.2 for masses and 1.35-1.36 for radii. This result supports similar previously obtained outcomes. The author extended the analysis with models constructed for the hadron-quark hybrid equations of state for the case of zero temperature and finite entropy per particle ($s = 3k_B$). The results confirm the universal relations mentioned with slightly different coefficients.

The Thesis includes some more interesting topics that incorporate the previously presented neutrino radiation hydrodynamics simulation methods to analyze neutron stars in accreting systems. Results of numerical analysis performed for the neutron star with an accreted envelope, and with a quark core that emerges in the neutron star interior, suggest the appearance of neutrinos with energies high enough to be detected.

As far as the language is concerned, I have no objections apart from some typos. There are, however, sentences that could be less complicated and perhaps divided into shorter ones, which would make them more transparent.

I have some remarks about the system of units used by the author. On page 45, the natural system of units $\hbar = c = 1$ is indicated. In other chapters, the system of units with $G = k_B = 1$ is also used. Adopting the natural system of units is evident because it facilitates calculations. However, writing all equations in standard units throughout the work would enable the author to avoid inconsistencies caused by a dual form of the notation, with and without physical constants, thus making it more transparent for the reader. On page 36, nuclear units are mentioned, and geometric units are mentioned in the caption of Figure 3.13. In the same context, I have to ask about the meaning of the sentence in the footnotes on page 174: "The units of the speed of light expressed in units of the speed of light, which is in the present notation c=1."

All the figures included in the Thesis are informative, with extensive captions. However, I have some comments:

In the caption of Figure 1.1, the progenitor, the ZAMS star with mass 18 $M_\odot$ should be marked as s18.0.

Figure 1.2 is placed in the Introduction, while the first reference I found is on page 80 in the caption of Figure 3.2. This is a bit inconvenient.

Figure 2.1 - The entropy per baryon should be written in lower case $s$, the index at the Boltzmann constant in upper case $k_B$.

In Figure 2.3b (Radial bounce profile), I do not see the green line corresponding to the omission of the neutron decay channel in the shell model calculations of Juodagalvis. In the caption of the exact figure, there is a velocity labeled $u$, while in the figure (panel b), the velocity is labeled $v$. A similar problem with velocity labeling occurs in Figure 4.1. In the Thesis, the velocity is sometimes named the radial velocity; a more appropriate term would be the radial velocity profile. The gray lines in Figures 4.3, 4.2, and 4.9 are faint. Especially the linear fits in Figure 4.9.

In Chapter 4, the author presents linear relationships between: $\rho_{collapse}$ and $t_{burst}$, $L_{\bar{\nu}_e,peak}$ and $E_{explosion}$, $\rho_{collapse}$ and $L_{\bar{\nu}_e,peak}$, $\rho_{collapse}$ and $\langle E_{\bar{\nu}_e}\rangle_{peak}$.

Table 4.5 also gives the linear fit coefficients between the individual quantities. The existence of these linear correlations is essential from the point of view of the possibility of using the appropriate relations to find constraints on the properties of dense nuclear matter. The author writes: "Combining the two linear correlations of equations (4.10) and (4.11) leads to a relation between the estimated explosion energy and the initial quark matter density $E_{explosion}$ and $\rho_{onset}$". The relations on page 133 show that the author should use equations (4.11) and (4.12). The transition from two regression equations to one is justified when the initial correlations, in this case (4.11) and (4.12), are strong enough; hence, it is essential for the author to provide the values of the Pearson correlation coefficients for relations (4.11) and (4.12). Regarding the notation of the mean energy in equation 4.13, the right bracket is written at the subscript level.

In Section 2.1, the author introduces the concepts necessary to describe general relativistic radiative hydrodynamics in spherical symmetry, starting with the introduction of comoving coordinates. My reservations concern the signature of the metrics 2.7 and 2.10. I also suggest checking equations 2.14 (the expression in parentheses should consist of the sum of two terms) and 2.20 (should be supplemented by a uH term). In equations 2.1 and 2.3, $e$ denotes the specific internal energy.

Additional remarks:

On page 28, at the beginning of the sentence: "At density around ..," there is an additional, unnecessary letter A.

On page 29, in the sentence "This process absorbs thermal energy... nucleons and protons", should be neutrons and protons

On page 67, a sentence beginning with "Finally, the whole kernel..." - fisvor - flavor On the same page, in the sentence " Currently, There are four scenarios..." there should be in lower case.

There are different versions of the word stratification - stratisfaction - stratifaction. On page 108 - emplozed - employed

All remarks mentioned above do not diminish the substantive value of the Thesis.

I strongly believe the Thesis deserves a distinction because of the effort put into obtaining such valuable results. The dissertation submitted by the candidate meets the statutory and customary requirements set for PhD theses. Therefore, I am pleased to recommend the candidate's admission to further stages of the due procedure for awarding a PhD degree.

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