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Editorial

The Nuclear Physics of Neutron Stars

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Neutron stars are considered extraordinary astronomical laboratories for the physics of nuclear matter as they have the most fascinating constitution of energy and matter in the Universe [1–3]. Recently, the detection of gravitational waves from the merging of two neutron stars in a binary neutron star system created a new opportunity for exploring the physics of neutron stars [4,5]. In particular, the majority of the static and dynamical processes of neutron stars are sensitively dependent on the equation of state of dense nuclear matter employed [6,7]. However, knowledge of the equation of state is very uncertain, especially at high densities; therefore, relevant predictions and estimations suffer. For example, there are strong speculations that a phase transformation from hadronic to quark matter takes place inside stars [8]. This theory needs to be thoroughly researched. Moreover, a long-standing goal in astrophysics is the determination of the maximum mass of neutron stars (both non-rotating and rotating) [9]. Neutron stars are directly related to the formation of black holes (Kerr black holes), connecting two of the most important astrophysical objects. As a consequence, the maximum mass of neutron stars is of great interest in studying the effects of both neutron stars and black holes on the dynamics of supernovae explosions. Furthermore, neutron stars, due to their compactness, may rotate very quickly compared to other astrophysical objects. In particular, the measurement of specific properties of rapidly rotating neutron stars (including their mass and radius, frequency, moment of inertia, and quadrupole moment) may lead to robust constraints on the equation of state as well as on the star's nuclear matter constitution at very high densities [10].

This Special Issue is a collection of various contributions dedicated to (a) modern applications of the theory of nuclear matter in neutron stars, (b) proposing ideas for constraining the equation of state for both and hot nuclear matter (low/high densities) with the help of recent observations as well as the detection of gravitational waves originating from neutron stars mergers, (c) relating the application of recent modified theories of gravity to the properties of neutron stars, (d) discussing some issues in relation to the astrophysical jets emerging from a wide variety of astrophysical compact objects, (e) discussing the possibility of the existence of exotic particles, including, for example, the hypothetical X17 boson in the interior of neutron stars, (f) presenting and analyzing the application of the so-called "pseudo-conformal model" that addresses dense compact star matter and is confronted with the astrophysical observables available at presents, and (g) exploring the existence of compact objects called "Ghost stars" endowed with arbitrarily small mass.

In contribution 1, the authors address the GW190814 Puzzle. In particular, the LIGO/Virgo collaboration observed a compact object with a mass of $2.59^{+0.08}_{-0.09}\ M_\odot$ as a component of a system in which the main companion was a black hole with a mass of 23 $M_\odot$ [11]. This observation immediately invited speculation as to whether this object falls into the neutron star–black hole mass gap. In any case, understanding nature of the GW190814 event will offer rich information concerning open issues, the speed of sound and possible phases transition into other degrees of freedom. The authors made an effort to examine possible constraints on the equation of state which were inferred from the consideration that the low-mass companion is a slow or rapidly rotating neutron star, also paying attention on the study of the tidal deformability and the radius of a possible

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high-mass candidate existing as an individual or component star in a binary neutron star system. They concluded that similar isolated neutron stars or systems may exist in the universe, and their possible future observation will shed light on the maximum neutron star mass problem.

The authors of contribution 2 proposed several constraints on the nuclear equation of state (EOS) currently available from neutron star (NS) observations and laboratory experiments and studied the existence of possible correlations among the properties of nuclear matter at saturation density using NS observables [12]. In particular, they used a set of different models that included several phenomenological EOSs based on Skyrme and relativistic mean field models as well as microscopic calculations based on different many-body approaches, i.e., the (Dirac–)Brueckner–Hartree–Fock theories, quantum Monte Carlo techniques, and the variational method. They concluded that while no correlation exists between tidal deformability and the value of nuclear symmetry energy at saturation for any NS mass value, very weak correlations seem to exist with the derivative of the nuclear symmetry energy and with the nuclear symmetry energy and with the nuclear incompressibility.

To overcome the problem that some Gogny-type [13] interactions lead to soft equations of state, the authors of contribution 3 built new Gogny parametrizations by modifying the density dependence of the symmetry energy predicted by the force in such a way that they could be applied to the neutron star domain and could also reproduce the properties of finite nuclei as well as their predecessors. These new parametrizations allowed the authors to obtain stiffer EOSs based on Gogny interactions which predict the maximum masses of neutron stars around two solar masses. Moreover, other global properties of stars determined, such as their moment of inertia and deformability, were in harmony with those obtained using other well-tested EOSs based on the SLy4 Skyrme force or the Barcelona–Catania–Paris–Madrid (BCPM) energy density functional.

Neutron stars are perfect candidates for investigating the effects of a modified gravity theory since curvature effects are significant and, more importantly, potentially testable. In most cases studied in the literature in the context of massive scalar–tensor theories, inflationary models were examined. The most important scalar–tensor model is the Higgs model, which depends on the values of the scalar field [14]. In view of the above, the author of contribution 4 investigated which potential form of the Higgs model is more appropriate for consistently describing a static neutron star. He proved numerically that the non-inflationary Higgs potential, which is valid for certain values of the scalar field in the Jordan frame, leads to extremely large maximum neutron star masses. Finally, he concluded that these results show the uniqueness of the inflationary Higgs potential since it is the only approximation for the Higgs model that provides self-consistent results.

The authors of contribution 5 examined collimated outflows of magnetized astrophysical plasma known as astrophysical jets, which have been observed to emerge from a wide variety of astrophysical compact objects. These systems can be considered either hydrodynamic (HD) or magnetohydrodynamic (MHD) in nature, which means that they are governed by non-linear partial differential equations [15]. The authors mainly focused on appropriate numerical solutions for the MHD (and/or RMHD) equations as well as a transfer equation for inside the jet and simulated multi-messenger emissions from specific astrophysical compact objects. They performed numerical simulations for neutrino, gamma ray, and secondary particle emissions. As concrete examples, they chose the galactic Cygnus X-1 and extragalactic LMC X-1 systems.

The authors of contribution 6 complemented the nuclear equation of state (EOS) with a hypothetical 17 MeV boson [16] and observed that only instances with an admixture of 30–40% satisfied all the relevant constraints. The successful EOS resulted in a radius of around 13 km for a neutron star with a mass of $M_{NS} \simeq 1.4\ M_{\odot}$ and a maximum mass of around $M_{NS} \simeq 2.5\ M_{\odot}$. They found that the value of the radius is in agreement with the recent measurement by NICER, while the maximum mass is also in agreement with the mass of the remnant of the gravitational wave event GW190814. They concluded that it appears that these EOSs satisfy all the existing experimental constraints and can be considered universal nuclear equations of state.

The author of contribution 7 discussed and analyzed the so-called "pseudo-conformal model" that addresses dense, compact star matter and is confronted with the astrophysical observables available at present, with a focus on those obtained from gravity waves [17]. Their predictions were made nearly free of parameters as the model involving "topology change" remained more or less intact and "un-torpedoed" by the data.

The authors of contribution 8 focused on computing the saturation properties of symmetric and asymmetric nuclear matter using the finite-range simple effective interaction with the Yukawa form factor [18]. The results of higher-order derivatives of the energy per particle and the symmetry energy computed at saturation were compared with corresponding values extracted from studies involving theory, experiments, and astrophysical observations. In particular, the ability of the resulting equations of state to predict the threshold mass for prompt collapse in a binary neutron star merger and gravitational redshift was examined in terms of the compactness of the neutron star and the level of incompressibility at the central density of the maximum-mass star. Finally, they analyzed and compared the correlations existing between neutron star properties and nuclear matter saturation properties with the predictions of other models.

In contribution 9, the authors explored an idea proposed many years ago by Zeldovich and Novikov concerning the existence of compact objects endowed with arbitrarily small mass [19]. The energy density of such objects, which are called "Ghost stars", is negative in some regions of the fluid distribution, producing a vanishing total mass. Thus, on the boundary surface, the interior is matched to Minkowski space-time [20]. The authors provided some exact analytical solutions and analyzed their properties. With the help of observational data, they confirmed or dismissed the existence of this type of stellar object.

In general, the study of neutron stars still has many open problems to address. These problems arise from different aspects of physics including nuclear physics, particle physics, the theory of gravity, and statistical physics. Solving these problems requires not only the expansion of theoretical study via the introduction of new ideas and models but also procurement of observational and experimental data via more systematic and extensive methods. Since the set of open problems–issues is quite large, we only some below. Regardless, new observations or the results of new experiments may provide answers to these problems and may also lead to the creation of new open issues. In summary, some of the key problems associated with the study of neutron stars and the physics behind them are as follows (also see the relevant Ref. [21]):

1. The experimental determination of nuclear symmetry energy close to and above the nuclear saturation density.
2. The hyperon "puzzle": the problem of the strong softening of the equation of state of dense matter induced by the presence of hyperons, which leads to a maximum mass value incompatible with observations.
3. The Bose condensation in nuclear matter: the effects of pion and kaon condensation in the interior of neutron stars.
4. Hadron–quark phase transitions in dense nuclear matter, which have implications for the structure of neutron stars.
5. Determining what other phases exist in the phase diagram of dense matter at low temperatures and how we can use neutron star observations to learn about these phases.
6. Hybrid stars as confirmations of phase transitions in dense nuclear matter: the twin star and backbending phenomena.
7. The possible existence of a mass gap between neutron stars and black holes and its implications for the formation of neutron stars.
8. The maximum and minimum masses of neutron stars; the maximum mass has implications for the minimum mass of a black hole and, consequently, the total number of stellar-mass black holes in our Universe, the progenitor mass, and the EOS of dense matter. The minimum mass is related to its formation through stellar evolution.

9. The accurate measurement of the radius of a neutron star. If possible, simultaneous measurements of the masses and radii of several individual stars could pin down an EOS free from the applied nuclear model.
10. Determining what limits the spin frequencies of millisecond pulsars and why; additionally, determining how effective mechanisms are for reducing the rotation speed of pulsars (r-modes, f-modes, etc.).
11. Determining how rich information from a neutron star cooling curve can be used, which microscopic mechanisms are responsible for this process, and what their roles are.
12. Investigating the mystery of the appearance of glitches and starquakes. What are the roles of superfluidity and the crust–core interface? What are the relevant dissipative processes?
13. Studying the neutron star–dark matter admixture and its application to the existence and possible determination of dark matter in the Universe.
14. Determining the origin of the strong magnetic field in neutron stars and elucidating the physics of magnetars.
15. Investigating neutron star mergers as a major source of gravitational wave radiation and the roles of star structure and deformability.
16. Investigating neutron star binary mergers: can they explain the creation (nucleosynthesis) and existence of heavy elements in the universe?
17. The lifetime and final-stage possibilities of binary neutron star merger remnants.
18. Determining the origin of X-rays on the surfaces of rapidly rotating neutron stars and the role of the strong magnetic field; investigating accreting neutron stars in binary star systems as the strongest sources of X-rays in our galaxy.
19. Investigating collisions between neutron stars as sources of short gamma-ray bursts, some of the most powerful and violent explosions in the known universe. What we can learn from the interiors of neutron stars?
20. Investigating exotic stars (quark stars, strange stars, pion stars, preon stars, Thorne–Zytkow objects, and gravastars): their origin, structure, observation, and verification.

Although the above list is quite extensive, we have robust indications that in the coming years, both improvements in experimental methods and the accuracy of astrophysical observations, in close cooperation with theoretical research, will provide solutions for the majority of the aforementioned open problems.

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Abbreviations

The following abbreviations were used in this manuscript:

NS	Neutron star
EOS	Equation of state

List of Contributions

1. Kanakis-Pegios, A.; Koliogiannis, P.; Moustakidis, C.C. Probing the Nuclear Equation of State from the Existence of a $\sim 2.6\ M_\odot$ Neutron Star: The GW190814 Puzzle. *Symmetry* **2021**, *13*, 183.
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