TYPE Editorial
PUBLISHED 13 May 2025
DOI 10.3389/fspas.2025.1613180

OPEN ACCESS

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RECEIVED 16 April 2025
ACCEPTED 28 April 2025
PUBLISHED 13 May 2025

CITATION
Zhang C, Huang Y, Xu R, Togashi H, Xia C and Rodin A (2025) Editorial: Neutron stars and quark stars inside out.
Front. Astron. Space Sci. 12:1613180.
doi: 10.3389/fspas.2025.1613180

Editorial: Neutron stars and quark stars inside out

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KEYWORDS

neutron star (NS), quark star, white dwarf, equation of state, stars, nuclear matter, quark matter, pulsar

Editorial on the Research Topic
Neutron stars and quark stars inside out

Since the theoretical proposal of neutron stars in the 1930s and the observational discovery of pulsars in the 1960s, neutron star physics has opened a new window on the extremes of the universe. With the simultaneous development of quantum chromodynamics in the 1970s, the hypothetical notion of strange quark matter and strange quark stars was born. In the 21st century, the physics of compact stars has been actively explored. In recent years, observational advances, in particular the detection of gravitational waves, have ushered in the era of multi-messenger astrophysics, improving our ability to probe the nature of these compact stars. However, there are still many challenges in this flourishing field. The equations of state are not firmly determined. The existence of hybrid stars associated with the hadron-quark phase transition is inconclusive. Distinguishing between neutron stars and quark stars remains a challenge.

The Research Topic "Neutron Stars and Quark Stars Inside Out" brings together cutting-edge investigations that shed light on the distinct characteristics of neutron stars and quark stars, in particular their internal compositions and observable manifestations. Spanning theoretical modeling, observational analysis, and computational approaches, the contributed articles collectively advance our understanding of compact stars on multiple fronts. This interdisciplinary field draws from nuclear physics, particle physics, general relativity, and astrophysics to address fundamental questions about the nature of matter under extreme conditions.

Zhang et al. provided a valuable overview of recent developments in the field of strange quark stars in their review article "*Recent progresses in strange quark stars*." Starting from the hypothesis that strange quark matter may be the true ground state of matter at extremely high densities, they introduced three popular phenomenological models that are widely used to describe strange quark matter, with special attention to the corresponding equation of state in each model. By combining these equations of state with the Tolman-Oppenheimer-Volkov equations, the authors demonstrated how the inner structure and the mass-radius relation can be determined for strange stars. The authors also explore tidal deformability and oscillations, which are sensitive to the composition and equations of state, and discuss hybrid stars as a special type of quark star. Of particular note is their discussion of gravitational wave emissions, which can be generated by strange stars through a variety of mechanisms, potentially providing a means of observably identifying these objects. The authors also highlighted how close-in strange quark planets could provide a unique test for the existence of strange quark objects, and how electromagnetic bursts, such as short gamma-ray bursts and fast radio bursts, could be generated by strange stars.

Xia et al. addressed an intriguing puzzle in their article "*Ultra-low-mass and small-radius white dwarfs made of heavy elements*." They examined seven recently identified ultra-low-mass and small-radius white dwarfs with masses ranging from ~0.02 to ~0.08 solar masses and radii from ~4,270 to 10,670 km. These measurements challenge traditional white dwarf models that assume a composition of primarily light elements such as carbon, oxygen, and helium. The authors proposed that these anomalous white dwarfs may instead be composed of heavier elements such as iron, nickel, palladium, and lead. They demonstrated that the smaller charge-to-mass ratios in heavy elements effectively reduce the electron number density in white dwarf matter, which reduces the pressure with additional contributions from lattice energy and electron polarization corrections. This mechanism elegantly explains the observed smaller masses and radii. The authors also suggested that this composition could account for sub-Chandrasekhar progenitors in underluminous Type Ia supernovae, addressing another observational puzzle. They compared their model with alternative explanations involving strange quark matter or quark nuggets, and emphasized the need for further observations through spectroscopy and asteroseismology to determine the true composition of these unusual white dwarfs.

In "*Hadron-quark phase transition in the neutron star with vector MIT bag model and Korea-IBS-Daegu-SKKU functional*," Sen et al. investigated the critical transition between hadronic and quark matter in neutron stars. Employing the Korea-IBS-Daegu-SKKU (KIDS) density functional for the hadron phase and the MIT bag model with the vector (vBag) model for the quark phase, they obtained hadron-quark phase transitions considering the Maxwell construction. The authors computed the structural properties of the resulting hybrid stars for three different values of the bag constant in the range $B^{1/4}$ = (145–160 MeV). Their study reveals that the symmetry energy has an important influence not only on the transition properties such as transition mass, transition radius, and density jump due to phase transition, but also on the stability of hybrid stars. Furthermore, they demonstrated that vector repulsion in the quark phase has a profound influence on obtaining reasonable hybrid star configurations consistent with recent astrophysical constraints. Their work effectively constrains the vector coupling constant to be $0.3 \lesssim G_V \lesssim 0.4$ for reasonable hybrid star configurations within their studied range of bag constants.

In "*Search for thermonuclear burst oscillations in the Swift/BAT data set*," Li et al. conducted a comprehensive analysis of the type I X-ray bursts observed by Swift/BAT from 2005 to April 2024. Their study focused on X-ray burst oscillations (XBOs), which are periodic signals detected within these bursts that typically range from 11 to 620 Hz. Using the high-sensitivity and precise timing capabilities of Swift/BAT, the authors identified 50 type I X-ray bursts from 37 neutron star low-mass X-ray binaries. For sources with known burst oscillation frequencies, their findings largely corroborate previous studies, although many sources displayed low confidence levels in the oscillation signals. More significantly, for sources without known oscillation or spin frequencies, their FFT analysis revealed potential oscillation signals over a broad frequency range, with several bursts showing significance levels exceeding 3σ.

Bernal et al. presented a complementary model to the well-established canonical model for the spin evolution of rotation-powered pulsars in "*On the overall properties of young neutron stars: an application to the Crab pulsar*." Their research report analytically explored the growth of the magnetic field during a pulsar's early history, a period shortly after the supernova explosion when the neutron star forms. This encompasses the hypercritical phase and subsequent re-emergence of the magnetic field, analyzing the impact of such growth on the early dynamics of the pulsar. The authors expanded existing knowledge by examining the evolutionary implications in a scenario governed by growth functions. Their proposed growth functions, calibrated with data from the Crab pulsar, exhibit satisfactory physical behavior. This work provides valuable insights into how the periodicity of pulsars might be altered during early development, contrasting with the assumption of stable, unchanging periodicity in the canonical model, and helps to explain observations of young neutron stars that do not adhere strictly to the rotating magnetic dipole model.

Collectively, these articles highlight the rich interplay between theoretical modeling and observational constraints in advancing our understanding of neutron stars, quark stars, and related compact objects. They demonstrate how multi-messenger astronomy, combining electromagnetic observations with gravitational wave detections, is crucial for resolving outstanding questions about the internal composition and structure of these objects. The research presented here has significant implications for fundamental physics, potentially informing our understanding of quantum chromodynamics, the nuclear equation of state, and the behavior of matter under extreme conditions.

Author contributions

CZ: Writing – original draft. YH: Writing – review and editing. RX: Writing – review and editing. HT: Writing – review and editing. CX: Writing – review and editing. AR: Writing – review and editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This research was funded by the National Natural Science Foundation of China (grant Nos 12233002, 12041306, 12275234), by the National SKA Program of China (No. 2020SKA0120300), and by the National Key R&D Program of China (2021YFA0718500). YH also acknowledges the support from the Xinjiang Tianchi Program.

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