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Review

Pulsars as astrophysical laboratories for nuclear and particle physics

F. Weber[a,*], R. Negreiros[a], P. Rosenfield[a], M. Stejner[a,b]

[a] *Department of Physics, San Diego State University, 5500 Campanile Drive, San Diego, CA 92182, USA*
[b] *Department of Physics and Astronomy, University of Aarhus, Ny Munkegade, DK-8000 Aarhus C, Denmark*

Abstract

A forefront of research concerns the exploration of the properties of hadronic matter under extreme conditions of temperature and density, and the determination of the equation of state – the relation between pressure, temperature and density – of such matter. Experimentally, relativistic heavy-ion collision experiments enable physicists to cast a brief glance at hot and ultra-dense matter for times as small as about 10^{-22} s. Complementary to this, the matter that exists in the cores of neutron stars, observed as radio pulsars, X-ray pulsars, and magnetars, is at low temperatures but compressed permanently to ultra-high densities that may be more than an order of magnitude higher than the density of atomic nuclei. This makes pulsars superb astrophysical laboratories for medium and high-energy nuclear physics, as discussed in this paper.

Keywords: Nuclear matter; Quark matter; Neutron stars; Pulsars; Strange stars

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1. Introduction

Exploring the properties of hadronic matter under extreme conditions of temperature and density has become a forefront of modern physics, both theoretically and experimentally. On the earth, heavy ion experiments enable physicists to cast a brief glance at such matter for times as small as about 10^{-22} s. On the other hand, it is well known that galaxies like our Milky Way contain up to 10^8–10^9 neutron stars, which are observed as pulsars (rotating neutron stars). Such

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[*] Corresponding author. Tel.: +1 619 594 0239; fax: +1 619 594 5485.
E-mail address: fweber@sciences.sdsu.edu (F. Weber).

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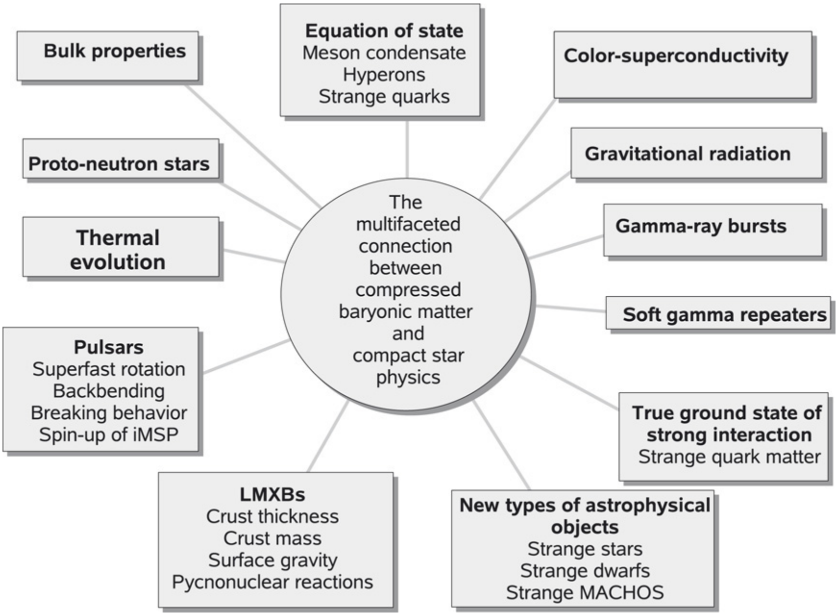

Fig. 1. The multifaceted connection between compressed baryonic matter and pulsar physics [6].

objects contain ultra-dense hadronic matter as a permanent component of matter in their centers. Radio telescopes, X-ray satellites, and soon the latest generation of gravitational-wave detectors, provide physicists and astronomers with an unprecedented wealth of high-quality data on such objects and thus serve as observational windows on the inner workings of pulsars. This feature makes pulsars superb astrophysical laboratories for medium and high-energy nuclear physics (plus other fields of physics) [1–8]. Some of the key questions that can be addressed by studying the properties of pulsars are (see Fig. 1):

- What are the fundamental building blocks of cold ultra-dense matter? Specifically, does “exotic” matter exist in the cores of pulsars, such as boson condensates, color-superconducting quark matter, and multi-quark states?
- Are there pulsar observables that could signal the existence of exotica in their cores?
- Are there rotationally-driven (accretion-driven) phase transitions in pulsars?
- How does color-superconducting quark matter alter the properties of pulsars?
- What is the true ground state of the strong interaction? Is it ordinary nuclear matter (i.e. atomic nuclei) or a color-neutral collection of up, down, and strange quarks (so-called strange quark matter)?
- What distinguishes pulsars made of strange quark matter from pulsars made of ordinary hadronic matter?
- What are the properties of matter subjected to ultra-high density radiation fields, ultra-high magnetic fields, ultra-high electric fields? How do such fields alter the properties of pulsars?
- What are the key nuclear (heavy ion) reactions in the non-equilibrium crusts of accreting X-ray pulsars?
- How strongly do pycnonuclear reactions in the crusts of accreting neutron stars alter the thermal evolution of such objects?
- Do gravitational-radiation reaction driven instabilities limit the spins of pulsars?