Image of Crab nebula from Hubble space telescope

Dense Matter, Compact Stars and Fundamental Physics

Our research group works on **dense matter and compact stars**, with a particular focus on neutron stars as natural laboratories for investigating the fundamental properties of matter under extreme conditions. Neutron stars are the compact remnants of massive stars formed in supernova explosions. With masses comparable to or greater than that of the Sun compressed into radii of only about 10–12 km, they provide a unique environment for studying matter at densities and pressures far beyond those accessible in terrestrial laboratories.

Equation of State of Dense Matter

A central focus of our research is the **equation of state (EOS) of dense matter**, which describes the relationship between pressure, energy density, and other thermodynamic properties of matter. The EOS plays a crucial role in determining the internal composition and macroscopic structure of neutron stars.

We develop and investigate theoretically consistent models of dense matter, including **modified MIT bag models and quasiparticle approaches**, and study their implications for neutron-star properties. Our research examines the dependence of the EOS on density and explores how different microscopic descriptions affect the **mass–radius relation, maximum mass, stability, and tidal deformability** of compact stars.

We also investigate the **speed of sound in dense matter**, an important quantity that characterizes the stiffness of the EOS and provides insight into the microscopic behavior of matter at supranuclear densities. Understanding its density dependence is particularly relevant for determining which theoretical models are compatible with the existence of massive neutron stars and current astrophysical observations.

Quark Matter and Hybrid Stars

At sufficiently high densities, ordinary hadronic matter may undergo a transition to **deconfined quark matter**. This possibility provides an important connection between compact-star physics and the fundamental theory of strong interactions.

Our group studies **hadron–quark phase transitions, quark stars, and hybrid stars**. Hybrid stars may contain a quark-matter core surrounded by hadronic matter, while quark stars are expected to be composed predominantly of deconfined quark matter. We investigate how the properties of these exotic phases modify the EOS and affect the mass, radius, stability, and tidal response of compact stars.

An important goal is to identify possible **observational signatures of quark matter** and determine whether astrophysical measurements can distinguish hybrid or quark stars from conventional neutron stars.

Dark Matter in Neutron Stars

We also explore the possible role of **dark matter in neutron stars**. Since the microscopic nature of dark matter remains unknown, compact stars provide a promising environment in which its interactions with ordinary matter may leave observable effects.

Our studies investigate the **capture and accumulation of dark matter inside neutron stars** and examine how its presence may modify the EOS, stellar structure, maximum mass, stability, and evolution of compact stars. These investigations provide a link between particle-physics models of dark matter and astrophysical observations.

Neutron-Star Oscillations

Another important area of our research is the study of **neutron-star oscillations and asteroseismology**. Neutron stars can support a variety of oscillation modes that may be excited by rotation, starquakes, accretion, mergers, or other external disturbances.

Since the frequencies and properties of these modes depend on the internal structure and composition of the star, oscillations can provide valuable information about the EOS and the physics of matter at supranuclear densities. We investigate these modes with the aim of establishing connections between theoretical predictions and potentially observable astrophysical signals.

Warm Stellar Matter

Theoretical studies of nuclear properties in warm stellar matter are being carried out within the Nuclear Statistical Equilibrium (NSE) framework, with applications to supernovae and proto-neutron stars. The research focuses on the composition, thermodynamic properties, and role of nuclear clusters under the extreme density and temperature conditions encountered in these astrophysical environments.

Connecting Theory with Observations

An important component of our research is the comparison of theoretical models with **multimessenger observations of neutron stars**. In particular, measurements from the **NICER**

mission provide constraints on neutron-star masses and radii, while **gravitational-wave observations** of compact-binary mergers provide information about tidal deformability and the behavior of dense matter.

By combining these observational constraints with theoretical EOS modeling, we aim to identify viable descriptions of dense matter and explore possible evidence for exotic phases such as quark matter.

Research Perspective

Our overall research brings together **nuclear physics, particle physics, astrophysics, and gravitation** to develop a deeper understanding of compact stars. By studying the EOS of dense matter, quark and hybrid stars, dark-matter effects, neutron-star oscillations, and multimessenger observations, we seek to understand how microscopic physics determines the macroscopic properties of some of the most extreme objects in the Universe.

Ultimately, our goal is to use neutron stars as **cosmic laboratories for probing fundamental physics**, and to uncover the nature and behavior of matter under conditions that cannot be reproduced on Earth.