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Hyperons and neutron stars

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Abstract

In this work we briefly review some of the effects of hyperons on neutron and proto-neutron star properties. We revise the problem of the strong softening of the EoS, and the consequent reduction of the maximum mass, due to the presence of hyperons, a puzzle which has become more intriguing due the recent measurements of the unusually high masses of the millisecond pulsars PSR J1614-2230 ($1.97 \pm 0.04 M_\odot$) and PSR J1903+0327 ($1.667 \pm 0.021 M_\odot$). We examine also the role of hyperons on the cooling properties of newly born neutron stars and on the so-called r-mode instability.

Keywords: Equation of state; Neutron stars; Hyperons

1. Introduction

Neutron stars are the remnants of the gravitational collapse of massive stars during a type-II, Ib or Ic supernova explosion. Their masses and radii are typically of the order of 1–$2M_\odot$ ($M_\odot \simeq 2 \times 10^{33}$ g is the mass of the Sun) and 10–12 km, respectively. With central densities in the range of 4–8 times the normal nuclear matter saturation density, $\epsilon_0 \sim 2.7 \times 10^{14}$ g/cm^3 ($\rho_0 \sim 0.16$ fm^{-3}), neutron stars are most likely among the densest objects in the Universe [1]. These objects are an excellent observatory to test our present understanding of the theory of strong interacting matter at extreme conditions, and they offer an interesting interplay between nuclear processes and astrophysical observables. Conditions of matter inside neutron stars are very different from those one can find in Earth, therefore, a good knowledge of the Equation of State (EoS) of dense matter is required to understand the properties of neutron stars. Nowadays,

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it is still an open question which is the true nature of neutron stars. Traditionally the core of neutron stars has been modeled as a uniform fluid of neutron-rich nuclear matter in equilibrium with respect to the weak interaction (β-stable matter). Nevertheless, due to the large value of the density, new hadronic degrees of freedom are expected to appear in addition to nucleons. Hyperons, baryons with a strangeness content, are an example of these degrees of freedom. Contrary to terrestrial conditions, where hyperons are unstable and decay into nucleons through the weak interaction, the equilibrium conditions in neutron stars can make the inverse process happen. Hyperons may appear in the inner core of neutron stars at densities of about 2–$3\rho_0$. At such densities, the nucleon chemical potential is large enough to make the conversion of nucleons into hyperons energetically favorable. This conversion relieves the Fermi pressure exerted by the baryons, and makes the EoS softer. As a consequence, the maximum mass of the star is substantially reduced. Other neutron star properties, such as their thermal and structural evolution, can be also very sensitive to the composition, and therefore to the hyperonic content of neutron star interiors. In particular, the cooling of neutron stars may be affected by the presence of hyperons, since they can modify neutrino emissivities and can allow for fast cooling mechanisms. Furthermore, the emission of gravitational waves in hot and rapidly rotating neutron stars due to the so-called r-mode instability can also be affected by the presence of hyperons in neutron stars, because bulk viscosity of neutron star matter is dominated by the contribution of hyperons as soon as they appear in the neutron star interior. In the following we briefly review the implications of hyperons on the EoS and several neutron star properties.

2. Hyperons, the maximum mass of neutron stars and "the hyperon puzzle"

Since the pioneer work of Ambartsumyan and Saakyan [2] the presence of hyperons in neutron stars has been studied by many authors using either phenomenological [3,4] or microscopic [5–7] approaches of hyperonic matter. Phenomenological approaches, either relativistic or non-relativistic are based on effective density-dependent interactions which typically contain a certain number of parameters adjusted to reproduce nuclear and hypernuclear observables, and compact star properties. Relativistic mean field models [3] and Skyrme-type interactions [4] are among the most commonly used ones within this type of approach. Microscopic approaches, on the other hand, are based on realistic two-body baryon–baryon interactions that describe the scattering data in free space. These realistic interactions have been mainly constructed within the framework of a meson-exchange theory [8,9], although recently a new approach based on chiral perturbation theory has emerged as a powerful tool [10]. In order to obtain the EoS one has to solve then the complicated many-body problem [11]. A great difficulty of this problem lies in the treatment of the repulsive core, which dominates the short-range behavior of the interaction. Various methods have been considered to solve the nuclear many-body problem: the variational approach [12], the correlated basis function (CBF) formalism [13], the self-consistent Green's function (SCGF) technique [14], or the Brueckner–Bethe–Goldstone (BBG) [15] and the Dirac–Brueckner–Hartree–Fock (DBHF) theories [16]. Nevertheless, although all of them have been extensively applied to the study of nuclear matter, up to our knowledge, only the BBG theory in the Brueckner–Hartree–Fock (BHF) approximation [5], and very recently the DBHF theory [6], and the $V_{low\,k}$ approach [7], have been extended to the hyperonic sector.

All these approaches agree that the appearance of hyperons at around 2–$3\rho_0$ leads, as said in the introduction, to a softening of EoS and consequently to a reduction of the maximum mass. In microscopic calculations [5,7], however, this reduction can be even below the "canonical" one of 1.4–$1.5M_\odot$ inferred from precise neutron star mass determinations [17]. This is not the