Strangeness in Astrophysics

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Abstract. In this contribution the role of strangeness in astrophysics is discussed and, more precisely, strange hadronic matter in the interior of neutron stars. A special attention is payed to certain phenomena involving strange hadronic matter, such as the hyperon puzzle, kaon condensation and the thermal behaviour of hyperons in neutron star mergers.

1 Introduction

Compact stars and, more precisely, neutron stars (NSs) are an excellent laboratory to study matter under extreme conditions of density, isospin asymmetry and temperature [1, 2]. NSs result from core-collapse supernovae and are in hydrostatic equilibrium with the gravitational collapse counterbalanced by the pressure inside NSs. NSs usually have masses around 1-2 $M_\odot$ and radii about 10-12 km, with an onion-like configuration. The largest region of an NS is the inner region, whose composition is not known. Thus, several hypothesis have been put forward to describe the NS interior.

Among others, hadronic matter made of strange baryons (also called hyperons) and/or strange mesons (mainly antikaons) has been postulated as possible scenarios in the inner core of NSs. In this contribution we aim at reviewing some specific phenomena related to the presence of strange hadronic matter inside NSs, such as the hyperon puzzle, the possible existence of kaon condensation as well as the thermal behaviour of hyperons as a possible indicator of their presence in NS mergers.

2 The hyperon puzzle

Hyperons are baryons with one or more strange quarks, such as Λ, Σ and Ξ. Since the seminal work of Ref. [3], hyperons have been thoroughly studied in the inner core of NS (for recent reviews see [1, 2, 4, 5]). NSs are charged neutral objects equilibrated by weak interactions involving the different species inside the core (β-equilibrium). The equilibrium can be expressed in terms of the chemical potentials of the different components. In particular, hyperons are expected to appear in the interior of NSs at densities of $\approx$ 2-3ρ_0, as the nucleon chemical potential could be so large at these densities that is energetically more favourable

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to have hyperons rather than highly energetic nucleons at the top of the Fermi seas. As a consequence, matter becomes softer when only nucleons are present as the system relieves Fermi pressure. Hence, the less pressure there is inside an NS, the less mass it can sustain. The softening of the equation of state (EoS) of matter could then lead to maximum masses not compatible with $2M_{\odot}$ measurements, such as the masses of the PSR J1614-2230 [6, 7], PSR J0348+0432 [8] and PSR J0740+6620 [9]. This fact is usually denoted as *the hyperon puzzle*. There is, however, no solution yet to this puzzle, although several answers have been put forward in order to have hyperons in the interior of $2M_{\odot}$ NSs.

Among them, one solution considers stiff hyperon-nucleon and hyperon-hyperon interactions so as to compensate for the softening of the EoS (see, for example, [10–13]). Another way for stiffening the EoS relies on the three-body forces [14–22]. Another solution pushes hyperons to larger densities by the occurrence of new species, such as Δ baryons [23–25] or a kaon condensate (as discussed in the following section). Also, solutions based on non-hadronic degrees of freedom have been considered, such as an early phase transition to quark matter below the hyperon onset (see Refs. [26–30] for recent papers). And, finally, modified gravity theories allowing for hyperons inside $2M_{\odot}$ stars have been also described in the literature [31].

3 Kaon condensation in neutron stars

Another possibility for strange hadronic matter is to consider strange mesons, such as antikaons in the core of NSs. As mentioned before, the composition of matter in NSs is determined by demanding β-equilibrium. In the particular case of matter made of neutrons, protons and electrons, the chemical potential of the electron substantially increases with density. Thus, antikaons could be produced if their effective mass gets smaller than the electron chemical potential at a given density inside NSs. In that case, antikaons would appear forming a condensate, hence leading to the phenomenon of *kaon condensation*.

Since the pioneering work of Ref. [32], this phenomenon has been widely discussed. The question is whether the mass of antikaons could be largely modified in nuclear matter. Whereas this is the case for some phenomenological models (see the recent results in Refs. [33–36]), microscopic unitarized schemes do not obtain such large modifications in the antikaon mass (see, for example, Refs. [37–44]).

4 Thermal behaviour of hyperons in neutron star mergers

In spite of the previous scenarios where strange hadronic matter might be present inside an NS, there is still the open question whether there is a clear signal of the presence of strange hadronic matter, and in particular hyperons, in NSs. For example, by comparing the mass-radius relations coming from EoSs with only nucleons or with nucleons and hyperons, it is not straightforward to tell from a measured mass-radius relation if the underlying EoS contains hyperons. Therefore, it is very much welcome to identify NS features that can be clearly linked to the appearance of hyperons in NS.

Recently, the *thermal behavior of hyperons* has been proposed as a potential indicator for the presence of hyperons in NS mergers [45]. The approach is based on the fact that the hyperonic EoSs produce lower average thermal indeces in matter than the nucleonic ones [46, 47]. The influence of the different thermal treatment on the dominant postmerger GW frequency is then systematically investigated using numerical simulations [45].

First, this frequency is obtained by running simulations using the full temperature- and composition-dependent nucleonic and hyperonic EoSs. Then, in another set of simulations,

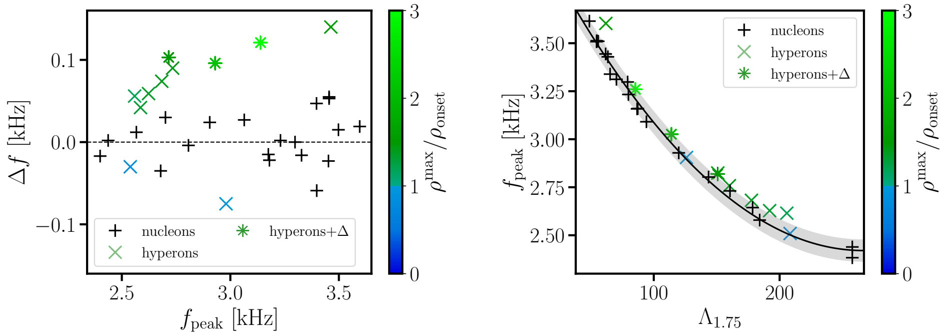

Figure 1. Left plot: $\Delta f = f_{\text{peak}} - f_{\text{peak}}^{1.75}$ as a function of f_{peak}. Right plot: f_{peak} of 1.4-1.4 $M_\odot$ mergers as function of tidal deformability of a 1.75 $M_\odot$ NS. Black symbols depict purely nucleonic models, whereas crosses display hyperonic models and asterisks refer to models which include Δs. The coloring shows the ratio between the maximum rest-mass density in the postmerger remnant and the hyperon onset rest-mass density at zero temperature. Black curve on the right plot shows least-squares fit to purely nucleonic models, while grey band displays maximum residual of purely nucleonic models from the fit. Plots taken from [45].

all EoSs at zero temperature in neutrinoless β-equilibrium are used and supplemented with the ideal-gas treatment of thermal pressure with $\Gamma_{\text{th}} = 1.75$, mimicking the thermal behavior of purely nucleonic matter. And, finally, the dominant postmerger GW frequencies of the full EoS models, f_{peak}, with the frequencies $f_{\text{peak}}^{1.75}$ obtained from the $\Gamma_{\text{th}} = 1.75$ calculations are compared, so that $\Delta f \equiv f_{\text{peak}} - f_{\text{peak}}^{1.75}$ measures the deviation from an idealized nucleonic thermal behavior. The results are shown in the l.h.s of Fig. 1, distinguishing purely nucleonic and hyperonic models. A characteristic increase of the dominant postmerger gravitational-wave frequency by up to $\sim$ 150 Hz is observed with the hyperonic EoS models (with a sufficient amount of hyperons) compared to purely nucleonic ones, thus linking this effect to the occurrence of hyperons in NSs.

Also, regarding the identification of hyperons by a frequency shift within a more concrete detection scenario, it is interesting to relate f_{peak} from the simulations with the fully temperature-dependent EoSs as function of the tidal deformability of 1.75 $M_\odot$ NSs, as done in the r.h.s of Fig. 1.The dominant postmerger frequency of hyperonic models is characteristically increased compared to the nucleonic models, so that the presence of hyperons may be deduced by an increased postmerger frequency that is not compatible with a nucleonic EoS.

Some caveats from the previous analysis need, however, to be mentioned, such as the necessity of enough statistical power in GW measurements, the dependence on the abundance of hyperons and hyperon threshold, or the fact that other exotic degrees of freedom might lead to a similar frequency shift.

5 Conclusions

In this contribution certain phenomena associated to the occurrence of strange hadronic matter in the inner core of NSs have been presented. More precisely, we have reviewed the hyperon puzzle and the possible solutions as well as the potential existence of a kaon condensed phase in NSs. Furthermore, the thermal behaviour of hyperons in NS mergers has been discussed as a feasible indicator of strangeness in the inner core of NSs.

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