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ULTRA-DENSE MATTER IN NEUTRONS STARS: EXISTING CONSTRAINTS AND PROSPECTS

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Abstract. Modelling neutron stars is a complex task which depends on many ingredients, among others the properties of dense matter. Models of dense matter, relevant for the description of core-collapse supernovae, neutron stars and neutron star mergers have to cover large ranges in baryon number density, temperature and particle composition which are in large parts inaccessible to terrestrial experiments. The characteristics of matter change dramatically throughout, from a mixture of nucleons, nuclei, and electrons to uniform, strongly interacting matter containing nucleons, and possibly other particles such as hyperons or quarks. In this contribution I will present some implications of GW170817 on the EoS of dense matter.

Keywords: neutron stars

1 Introduction

The properties of compact stars, their formation as well as binary mergers depend on many different physical ingredients, among them the thermodynamic properties of the involved matter comprised in the equation of state (EoS). There is an intrinsic connection between the properties of matter contained in the EoS for the macroscopic description of astrophysical objects and the underlying fundamental interactions between particles on the microscopic level. This makes the study of the aforementioned systems very rewarding as they challenge our understanding of nature on both scales.

It is not an obvious task to construct such an EoS. The main difficulty arises from the fact that very large ranges of (baryon number) densities (10^{-10} fm$^{-3} \lesssim n_B \lesssim 1$ fm^{-3}), temperatures ($0 < T \lesssim 150$ MeV) and hadronic charge fractions ($0 < Y_Q = n_Q/n_B \lesssim 0.7$) have to be covered. n_Q here denotes the total hadronic charge density, which in many cases is just given by the proton density. Within this range, the characteristics of matter change dramatically, from an ideal gas of different nuclei up to uniform strongly interacting matter, containing in the simplest case just free nucleons and potentially other components such as hyperons, nuclear resonances or mesons. Even a transition to deconfined quark matter is possible, see Oertel et al. (2017) for a recent review.

After a brief summary of experimental, theoretical and observational constraints on the EoS, within this contribution I will focus on the impact of the recent observation of gravitational waves from a binary neutron star (NS) merger (GW170817) on the different EoS models, in particular those covering the full thermodynamic parameter range necessary to describe core-collapse supernovae and binary mergers ("general purpose" EoS).

2 Brief summary of theoretical, experimental and observational constraints

Since dense and hot matter can (presently) be described from first principles, i.e. starting from the theory of strong interactions, QCD, only in some restricted density, temperature and asymmetry regions, many uncertainties exist. Most models rely on phenomenological interactions, whose parameters have to be adjusted to existing experimental or observational data. Microscopic many-body calculations (Brueckner-Hartree-Fock, Monte Carlo techniques, renormalisation group, . . .) starting from the fundamental two- and three-body forces can to some extent constrain the phenomenological models, too. But since it is impossible to solve the strongly

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interacting many-body problem exactly, these calculations contain, in addition to the uncertainties on the fundamental forces, more or less controlled approximations and the constraints have to be regarded with some care.

On the experimental side, different coefficients of the Taylor expansion of the energy per baryon of symmetric nuclear matter (i.e. same number of protons and neutrons) can be determined from a variety of nuclear experiments. In particular these are the binding energy E_B, the saturation density n_0, the compression modulus K, the symmetry energy J and its slope L. It is very challenging to extract additional coefficients, such as the slope of the symmetry energy, and the corresponding error bars are large. From heavy ion collisions, flow data and meson production data, where the analysis within a transport model is reinterpreted as model for the equation of state, can give some indication, too. More details and a discussion of different studies can be found in Oertel et al. (2017).

On the astrophysical side, the main present constraint stems from observations of NS masses in different binary systems, see e.g. Özel & Freire (2016) for a compilation. In some of them the masses can be precisely determined from the orbital parameters of the system without much model dependence in the analysis. In particular, precise masses are known for several binary NS systems giving masses close to the canonical value of 1.4 $M_\odot$. Recently, two precise mass determinations in NS-white dwarf systems have been carried out. For the first system, the precise determination is based on Shapiro delay, a general relativistic effect, giving a mass of $1.928 \pm 0.017 M_\odot$ for the neutron star (Demorest et al. 2010; Fonseca et al. 2016). The second one combines a well-known model for the white dwarf with an analysis of orbital data to obtain a mass of $2.01 \pm 0.04 M_\odot$ for the neutron star (Antoniadis et al. 2013). These two solar mass neutron stars are probably not the end of the story since there are indications of even more massive ones in NS-brown dwarf systems (van Kerkwijk et al. 2011).

For pulsars, the rotation frequency can be determined very precisely, too, but for the moment the fastest known pulsar, PSRJ1748-2446ad, rotates at a frequency of 716 Hz (Hessels et al. 2006), well below the Kepler frequency for almost all EoS. Thus the constraint induced on the EoS is very weak. An observation of 1.4 kHz, on the other hand, would constrain the radius of a non-rotating 1.4 $M_\odot$ star to be below 9.5 km, very difficult to obtain for most existing EoS.

The ultimate constraint on the EoS would be a determination of radius and mass of the same object, see e.g. Steiner et al. (2010). So far, radius observations are, however, much more model dependent than mass measurements. They contain in general different assumptions e.g. on the composition of the atmosphere or the distance of the object and it is difficult to estimate the systematic error on the given values, see Fortin et al. (2015); Oertel et al. (2017) for a more detailed discussion. Many observational projects are underway or planned in order to determine radii more precisely. For instance, NICER, launched in June 2017, aims to determine radii to a precision of $\sim 5\%$. On the theoretical side it is important to stretch that prediction for radii are subject to non-negligible uncertainties if the underlying model does not describe crust and core in a unified way, i.e. with the same nuclear interaction Fortin et al. (2017).

There are other observations with possible impact on the EoS, but for the moment either the analysis is very model dependent or the observations have large error bars, such that not relevant constraint on the EoS can be obtained for the moment. An example is asteroseismology from the observation of quasi-periodic oscillations. It is of course possible that in the future interesting constraints can come from these studies.

Matter properties evidently do not resume to the EoS. Examples are the observation of pulsar glitches which clearly indicate a superfluid component inside neutron stars or the neutrino signal from core-collapse supernovae sensitive among others to neutrino-matter interactions and neutrino properties. A detailed description of all aspects goes beyond the scope of the present contribution.

3 GW170817 tidal deformability

The most promising recent progress in our understanding of the NS EoS clearly comes from gravitational wave observations of a binary neutron star merger, the event GW170817 (Abbott et al. 2017). The observed signal from the inspiral of the two stars allows to determine precisely the chirp mass, $\mathcal{M} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$ to $\mathcal{M} = 1.186(1) M_\odot$ (Abbott et al. 2018). The two individual masses m_1 and m_2 are more difficult to obtain, and the LIGO/Virgo collaboration quotes the following range for the mass ratio $0.73 < q = m_2/m_1 \leq 1$ (low spin prior) at 90% credible level (Abbott et al. 2018). The late inspiral contains in addition information on the tidal deformation of the stars. For a static, spherically symmetric star, placed in a static external quadrupolar tidal field $\mathcal{E}_{ij}$, the tidal deformability λ can be defined to linear order as (Hinderer et al. 2010)

$$Q_{ij} = -\lambda \mathcal{E}_{ij} \; , \tag{3.1}$$

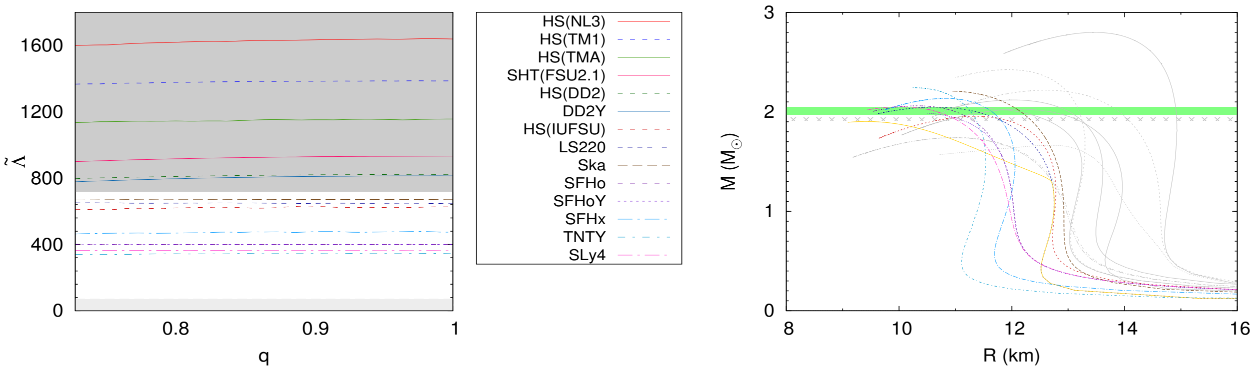

Fig. 1. (Color online) **Left:** Tidal deformability $\tilde{\Lambda}$ as function of the mass ratio of the two stars $q = m_2/m_1$ for GW170817 for different general purpose EoS models. The grey rectangles limit the regions excluded at 90% credible level by LIGO/Virgo (Abbott et al. 2017, 2018) using the low spin prior. **Right:** M-R relation for a cold, β-equilibrated spherically symmetric neutron star. The EoS models excluded either by the NS mass measurements or at 90% by GW170817 are indicated by grey lines.

where Q_{ij} represents the star's induced quadrupole moment. The actual signal is sensitive to a mass-weighted combination, $\tilde{\Lambda}$, of the two tidal parameters ,

$$\tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12\, m_2) m_1^4 \lambda_1 + (m_2 + 12\, m_1) m_2^4 \lambda_2}{(m_1 + m_2)^5} , \tag{3.2}$$

with a value of $\tilde{\Lambda} = 300^{+420}_{-230}$ (low spin prior) at 90% Abbott et al. (2018).

Fig. 1 (l.h.s.) displays the tidal parameter $\tilde{\Lambda}$ as function of the mass ratio q for several general purpose EoS models, see Oertel et al. (2017) for the acronyms and the original references*. The chirp mass has been fixed to the value given for GW170817. The uncertainty on the latter induces only a very small uncertainty on $\tilde{\Lambda}$, not visible on the plot. The same EoS model has been assumed for both stars and the zero temperature, β-equilibrated EoS has been employed. Additional uncertainties arise since it is not yet clear to which extent the two stars might be heated up and the elastic crust melted close to merger when $\tilde{\Lambda}$ is determined. Further work is thus necessary to quantify these effects.

From Fig. 1 (l.h.s) it is obvious that some of the EoS are excluded by the GW measurement. On the right hand side, the mass-radius relations of cold spherically symmetric β-equilibrated neutron stars for the general purpose EoS models are shown. Those models leading either to maximum masses below the observed ones or which are (at 90% level) not compatible with GW170817 are indicated by grey lines. Although there is no one-to-one relation between $\tilde{\Lambda}$ and NS radii (Sieniawska et al. 2018), it is obvious that in particular EoS models with large NS radii lead to too large values for $\tilde{\Lambda}$ and the results are in favor of a radius for a fiducial $M = 1.4 M_\odot$ star of $R_{1.4} \lesssim 13$km. Note that some of the nuclear matter parameters in the disfavored EoS models, in particular symmetry energy and slope present a tension with results from nuclear experiments, too.

4 Summary and Outlook

Much work has been devoted to the description and understanding of dense cold matter in neutron stars and hot and dense matter as it occurs in core-collapse supernovae and binary neutron star or neutron star-black hole mergers. Concerning the EoS, much progress has been achieved in recent years. One the one hand several new general purpose models have been constructed, enlarging the variety of nuclear interaction models, improving the treatment of clustered matter and including the possibility of additional particles, such as hyperons, mesons or quarks at high densities and temperatures.

On the other hand, theoretical, experimental and observational efforts help to much better constrain the EoS. In particular, two reliable observational constraints are now available. Firstly, the observation of two neutron stars with a mass of about $2 M_\odot$ has triggered intensive discussion on the composition of matter in

*The model labeled "TNTY" corresponds to the EoS from Ref. Togashi et al. (2017)

the central part of neutron stars and its EoS. In contrast to what has been conjectured in the beginning, these observations do not exclude the existence of other particles than neutrons, protons and electrons in the core. This observation, however, puts stringent constraints on the respective interaction. Different solutions with hyperonic and/or quark matter have been proposed without any definite conclusion.

Secondly, the measurement of the neutron star tidal deformability during the late inspiral of a binary neutron star merger with the event GW170817 puts additional stringent constraints on the EoS of NS matter and clearly excludes several models. It should be emphasized that these results are in agreement with indications from nuclear physics experiments and theory.

Future constraints are to be expected among others from the NICER NS radius determinations, additional precise NS masses, rotation frequencies and potentially moments of inertia from the SKA (Acero et al. 2017), and certainly from further GW detections from BNS mergers. In addition to the tidal deformability, the detection of the post-merger oscillation frequencies could give interesting constraints in the future (Sekiguchi et al. 2011; Bauswein et al. 2012, 2016, 2018).

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