Supernova and compact star simulations

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The present contribution concerns the following research fields (check the relevant boxes, multiple if needed):

☒ Nuclear astrophysics

☐ Nuclear structure and reactions

☐ Hadronic physics

☐ Particle physics

☐ Astro-particle physics

☒ Cosmology and gravitation

Abstract: Numerical approach is mandatory for the modeling of compact stars and core-collapse supernovae. Several research groups in France have developed and/or run such numerical models for the simulation of isolated neutron stars, core-collapse supernova together with their electromagnetic signals and the formation of proto-neutron stars. Of highest importance is the link between microscopic models for nuclear matter and those codes giving the global picture, in particular when it comes to determine, with a certain accuracy, observable multimessenger signals. Next decade will witness the construction of improved multi-messenger observatories, such as the LSST, Einstein Telescope and SNEWS, which will require improved accuracy in the numerical models.

TEXT (max 5 pages):

I. General viewpoint

Beside being exciting objects to study *per se*, core-collapse supernovas (CCSN) and compact stars represent extraordinary probes of nuclear matter in conditions that are not reachable in Earth-based experiments and among the most powerful sources of gravitational waves. On both of these aspects it is absolutely necessary to get detailed models of compact objects, which require numerical approaches, apart from the early inspiral phase of binary neutron star (BNS) systems where both stars can be considered as point particles. Complexity stems from the properties of these systems, such as the relativistic movements of matter (in CCSN and last stages of BNS fluid velocity can be of the order of several tenths of the speed of light), intense gravitational field (from the definition of compactness, general-relativistic effects are not negligible) and matter spanning large intervals in densities, temperatures and isospin asymmetries. All these aspects (plus possible other ones, such as neutrino transport, magnetic field or radiation transfer) must be carefully taken into account in the numerical models.

There exist several groups in the world who have acquired a large expertise in these simulations over the years, including French ones who take part in some of these collaborations. It must be noted here that although theoretical in spirit, numerical modeling shares many common points with experimental approaches, with the requirement of large facilities (high-performance computing – HPC – centers), the need for support from computer technicians and engineers and the long-lasting preparation (development) of sophisticated tools. The aim of this proposal is to briefly present efforts in numerical simulation dealing with compact stars and supernovae in France, as well as a tentative outlook. It has, of course, some overlap with other proposals focused on particular physical aspects (CCSN explosion mechanism, equation of state for dense matter, theoretical modeling of neutron star crust…), but is specific in terms of methodology.

II. Isolated (cold) neutron stars

Global modeling of isolated neutron stars has a longstanding tradition at the Observatoire de Paris, since the 1980's. A publicly available numerical library (LORENE) has been built to model compact objects in full General Relativity, using spectral methods [1]. More recently, much effort has been made to incorporate detailed microphysical models (e.g. equations of state – EoS – for nuclear matter) and the interplay between global model properties and the EoS, as for magnetic field dependent EoSs [2]. The numerical tool is also essential to connect matter microscopic properties to astrophysical observables, such as pulsar glitches where neutron superfluidity can determine glitch rise time [3]. In the same field, local (mesoscopic) models of neutron star crust are of great importance to determine observable properties of neutron stars and numerical solutions to superfluid hydrodynamics have been obtained [4]. Although none of these numerical simulations fall in the HPC category, they can often be quite CPU-time consuming when exploring large parameter spaces.

III. Core-collapse supernovas and proto-neutron stars

CCSN simulations are tremendously complex and demanding, as in principle full three-dimensional numerical models with accurate neutrino transport are required to describe in some details the explosion mechanism. Therefore, very few groups in the world have developed and are able to run such complete codes. However, simpler codes as CoCoNuT [5] (developed in collaboration with the group in Garching) or ACCEPT [6] (in collaboration with Valencia university) are useful, too as toy models to probe the influence of a given physical assumption/model onto the CCSN observables; e.g. the accuracy of the electron capture rate models as in [6]). In a similar spirit, the RAMSES code [7] has been used to study neutrino driven convection in CCSN in a two- or three-dimensional setting [8], but with very simple microphysics. Nevertheless, as far as the study of electromagnetic signals from supernovas are concerned CMFGEN [9], a state-of-the-art numerical tool for the modeling of radiative transfer, has been applied to simulations of magnetar-powered CCSN lightcurves [10]. Moreover, the recent *ERC starting grant* "MagBURST" has greatly enhanced the numerical activity on proto-neutron star formation during CCSN events and, in particular, numerical simulations of the growth of the magnetic field based on convection [11] and the magneto-rotational instability [12] in those objects, as well as the large scale structure of magnetar-driven explosions with the code AENUS ALCAR [13]. Finally, in order to correctly interpret neutrino signals from CCSN events and proto-neutron star cooling, it is important to incorporate into the models neutrino flavor conversion in such environments [14].

IV. Binary neutron stars

Similarly to CCSN numerical models, BNS merger simulations are quite demanding and there are not many existing codes simulating these events. Although there has not been any such code developed in France, initial data for these simulations can be computed using the LORENE library [1], and in addition to the library itself, several sets of initial data are available to the community. Many of the BNS simulations thus use these data. A general update of these data, using the more recent library KADATH [15], has been obtained in collaboration with the group in Frankfurt [16].

V. Microphysics input for numerical models

As stated previously, numerical meso/macroscopic models are absolutely necessary to make the link between microscopic calculations (EoSs, neutrino reaction rates, …) and (astro)physical observable quantities. However, the inclusion of the former in simulation codes is not always a trivial task. Indeed, matter microscopic properties are themselves the results of complex models requiring a large amount of computing time, and cannot be computed “on the fly” during global simulations. They are therefore computed in advance, and stored in tables, which are then read and their data interpolated by global simulation codes. In the description of nuclear matter, the lack of true *ab initio* calculations at high densities has resulted in a variety of approaches and models. In order for groups performing global simulations to be able to use these different microscopic models, the COMPOSE database [17] has been set up to provide a unified format and framework, with the support of European network within the COST actions “NewCompStar” and “PHAROS”. Another approach is to use analytic prescriptions of nuclear matter microphysical properties (e.g. the EoS) using empirical parameters that are then constrained by experimental and observational data [18]. This metamodeling approach gives a flexible tool, which is at the same time very convenient in numerical simulations.

VI. Summary – Outlook

French compact star and CCSN simulation community has gained very good expertise in several areas, such as accurate models of isolated neutron stars, simulation of astrophysical signals from supernovae, the study of instabilities in CCSN, formation of the proto-neutron star and the link between microphysical and global modeling. This has been made possible thanks to various international collaborations and networks. Some links with observational/experimental communities have already been established, for supernova electromagnetic signals (e.g. with the Vera Rubin Observatory), neutrino signals (e.g. with SNEWS network) or gravitational waves (LIGO-Virgo-Kagra) from BNS coalescence. On this last point, one can see a weakness in the community which is the lack of any group having the expertise in developing and/or running a code for the simulation of such phenomena. Although interesting results can be obtained in this context by models for initial data and simulations of the post-merger phase by a single (hypermassive) neutron star (see e.g. [19]), forthcoming (3^{rd} generation of) ground-based gravitational wave detectors such as

Einstein Telescope may require more detailed numerical models. Finally, the general context of HPC must not be neglected: the world largest supercomputing facilities are heading toward exascale capacities, demanding that HPC codes be able to run on such particular architectures. This important point or, more generally a good level of HPC, cannot be achieved without persistent support from computer engineers and technicians and a complete spectrum of HPC facilities available to researchers, from Tier-0 to Tier-2, and even local smaller clusters.

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