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SIMULATIONS OF STELLAR COLLAPSES TO BLACK HOLES: INFLUENCE OF HYPERONS

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Stellar core collapse to a black hole is an event where extremely high temperatures and densities are reached. It is then expected that additional particles to nucleons and electrons appear, as hyperons. We present numerical simulations of the collapse of massive stars to black holes, with an equation of state based on the Lattimer–Swesty one, but allowing for the presence of Λ hyperons. A feature of these equations of state is that its cold and beta-equilibrium version allows for neutrons stars with almost two solar masses, marginally compatible with recent observations. Spherically symmetric simulations, under some conditions, may show the effect of a phase transition to hyperonic matter before the appearance of the black hole. We show axisymmetric simulations, too, where this phase transition would be smoothed, but where gravitational waves show clear imprint of the presence of hyperons.

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INTRODUCTION

Stellar mass black holes form in the collapse of massive stars, which have reached the end of their evolution on the main sequence. As in the case of supernovae, these stars have built an iron core by nuclear burning of lighter elements. The beginning of the collapse of such massive stars is triggered by this iron core reaching its maximal mass and then, becoming unstable. As the core starts to collapse, outer layers follow and the whole star undergoes a catastrophic collapse until the central region (the protoneutron star) reaches about nuclear saturation density. Nuclear interaction becomes rapidly repulsive, inducing a bounce of the iron core outer layers, which propagate outwards and form a shock. The shock strongly heats the infalling material and looses energy through photodissociation of iron nuclei. In the supernova case, this shock manages

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in some (still unknown) way to get enough kinetic energy to escape from the star's gravitational potential well and to disperse the star's outer layers into the interstellar medium. On the other hand, if the shock is not able to get revived, it falls back onto the protoneutron star, which also accretes all the star's material, thus becoming too massive to sustain its own weight, thus collapsing to a black hole. This scenario is often invoked as a possible explanation for the central engine for the long-duration gamma-ray bursts (collapsar model).

Within this context, the collapse of a stellar core to a black hole has already been studied by various numerical simulations, among which one can cite the works by Sumiyoshi et al. [13], Fischer et al. [4] or Ugliano et al. [14]. The whole collapse can be divided into three phases: first the usual collapse and bounce, which are very similar to the supernova case, and last about a tenth of a second, then a relatively slow accretion of matter onto the protoneutron star, which can last about a second, and finally a rapid collapse to the black hole, when the protoneutron star has reached its maximal mass. In the last two phases, much higher densities, well above nuclear saturation density, and temperatures (few tens of MeV) are reached, as compared to supernova scenarios.

With such high densities and temperatures, it is expected that additional particles (observed on Earth) should appear. The questions that therefore arise and that we have tried to answer in our study (Peres et al. [10]) are the following: How many new particles could appear on the way to the black hole? What is their influence on the collapse? What is their observational signature, in particular, in terms of neutrinos or gravitational waves? Finally, this also leads us to the reverse question: can we infer nuclear matter properties from observation of black hole formation? To answer these questions, we have built a numerical code (Sec. 1) and an equation of state (EoS, Sec. 2), which are presented hereafter. Section 3 gives some of the results obtained in spherical and axial symmetry and the final section concluding remarks.

1. NUMERICAL MODEL

The simulations have been performed with a given number of simplifying hypotheses, mainly in order to reduce the computational cost. Therefore, the simulations presented here have been done either under spherical symmetry (1D) or axial symmetry (2D) hypothesis. However, as we are interested in the formation of a black hole, which is by definition a relativistic object, we have used general relativity as the theory for the description of gravitational interaction. In particular, we have used the so-called $3+1$ formulation, with the isotropic gauge in 1D and conformally flat condition (CFC) in 2D. In this last case, gravitational waves are extracted from the numerical results, with the use of the modified quadrupole formula. The detection of a black hole in our space-time was done with the call to an apparent horizon finder, from Lin & Novak [8]. The use of relativistic gravity implied a relativistic description of hydrodynamics, too, with the perfect fluid model for the stress-energy tensor. Our EoS is based on the work by Oertel et al. [9] and shall be described in Sec. 2. Deleptonization is taken into account through a simple advection equation for electrons and neutrinos, together with a neutrino leakage scheme, which shall be described later, too.

The code is based on the CoCoNuT[*] simulation program (see also Dimmelmeier et al. [3]), which can potentially perform simulations without any symmetry assumption but, as it is not yet fully operational in its parallel version, we have run it in 1D or 2D. The code uses high-resolution shock-capturing schemes for the relativistic hydrodynamics, which equations are written in a conservative form. Einstein equations in CFC result in a nonlinear coupled system of elliptic partial differential equations, which are solved using multidomain spectral methods (see, e.g., Grandclément & Novak [5]). As the two methods use different types of grids, an interpolation is performed between both, together with a filtering, in order to avoid the Gibbs phenomenon within spectral methods.

Neutrino leakage is based on the definition of two zones: one where the fluid is opaque to neutrinos, which are then considered as fluid, too; and the other where the fluid is transparent and neutrinos are free-streaming. Thus, no transport is computed, which saves a lot of computing time, but implies a large number of approximations and drawbacks. In particular, there is no semitransparent regime and no self-consistent heating mechanism; this approach cannot revive the stalled shock, but is rather well-suited for the case of collapse to a black hole. Optical depths are nevertheless required, and are computed for three species of neutrinos (ν_e, $\bar{\nu_e}$ and ν_x for all other neutrino species). Losses of energy and momentum are taken into account.

2. EQUATION OF STATE

Nuclear models for collapse simulations are scarce, and exhibit large uncertainties, in particular, because nucleon–nucleon interaction is difficult to model. In this study, we have used a generalization of the EoS by Lattimer & Swesty [7], with an effective (Skyrme-type) model for the nucleon–nucleon interaction. In this approach, matter is made of neutrons, protons, electrons, positrons, photons, α particles and a mean nucleus A, representative of the nuclear statistical distribution. Among the parameters involved in the definition of the Lattimer & Swesty EoS, we have chosen the incompressibility to be $K = 220$ MeV, the others are taking values constrained by nuclear experiments performed at saturation density for symmetric matter. This EoS is called **LS220** in the rest of the text.

To this EoS, we have added other particles, which are well-known from particle accelerators and heavy-ion colliders: *pions* and *hyperons*. From our

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[*] http://www.uv.es/coconut.

current knowledge of these particles, they should appear in core-collapse phenomena. There are thus two new EoSs: **LS220 + pions**, where pions π^-, π^0 and π^+ have been added as a free gas; and **LS220 + hyperons**, in which only Λ hyperons have been considered with an interaction from Balberg & Gal [1], and which contains a first-order phase transition to hyperonic matter (see also Oertel et al. [9] and Gulminelli et al. [6] for more details). Note that in these EoSs, the hadronic interaction differs from previous studies with additional particles (e.g., Sumiyoshi et al. [13]), where a relativistic mean-field model was used.

A usual problem with EoSs containing hyperons is that, if no hyperon–hyperon interaction is present, the maximal mass for cold neutron stars with such an EoS is about $1.4M_\odot$, which is absolutely incompatible with recent observations of $\sim 2M_\odot$ neutron stars (e.g., Demorest et al. [2]). A solution to this problem may be to let quarks appear early enough so that no hyperon is present at neutron star densities, or to stiffen the EoS through short-range repulsion in the hyperon–hyperon interaction. With this last approach, we have computed static neutron stars at zero temperature and found the maximal mass for EoS **LS220 + pions** to be $M_{\max} = 1.95M_\odot$ and for EoS **LS220 + hyperons**, $M_{\max} = 1.91M_\odot$, making them marginally compatible with observations. A better exploration of the EoS parameter space could still improve the maximal masses for cold neutron stars.

As far as neutrino interactions are concerned, the following reactions have been considered. Creation processes (N stands for a given nucleus, of atomic numbers (A, Z)):

- $p + e^- \to \nu_e + n$,
- $(A, Z) + e^- \to (A, Z - 1) + \nu_e$,
- $e^- + e^+ \to \nu_i + \bar{\nu}_i$,
- $\tilde{\gamma} \to \nu_i + \bar{\nu}_i$,

and opacity processes:

- $\nu_i + N \to \nu_i + N$,
- $\nu_i + (A, Z) \to \nu_i + (A, Z)$,
- $\nu_e + n \to p + e^-$,
- $\bar{\nu}_e + p \to n + e^+$.

3. RESULTS

We have performed several simulations, starting from a progenitor star of $40M_\odot$ at zero age on the main sequence, as described in Woosley et al. [16]. Runs in 1D have been performed with the **LS220 + pions**, for which we have observed a maximal pion fraction $Y_{\pi^-} = 0.13$ at the onset of black hole collapse. Moreover, we had $Y_{\pi^-} > Y_{\pi^0} > Y_{\pi^+}$ at all times. Results for this EoS are displayed in Fig. 1, *a*, together with the reference run using EoS **LS220**. The protoneutron star with **LS220 + pions** seems more compressible, which means that there is less pressure and, therefore, it cannot hold as much mass as with

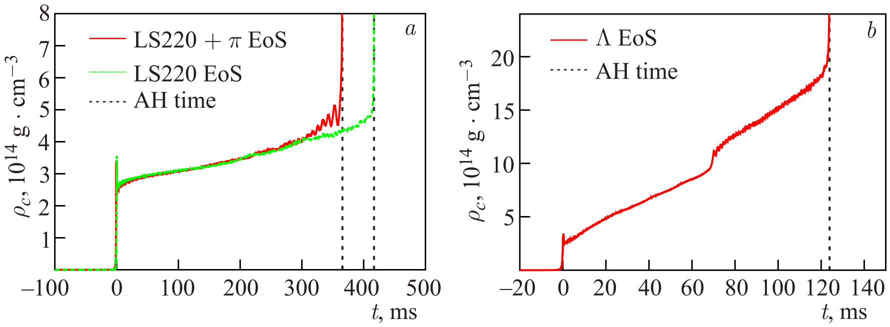

Fig. 1. Evolutions of the central density in the star as functions of time for 1D simulations using EoSs **LS220** and **LS220 + pions** (*a*, dashed and solid lines, respectively) and for EoS **LS220 + hyperons** (*b*). Vertical dashed lines denote the time of formation of the black hole

EoS **LS220**: it collapses faster to the black hole. This is confirmed by looking at the protoneutron star baryonic mass at the moment of collapse to the black hole: $M_B = 2.55M_\odot$ with **LS220** and $M_B = 2.49M_\odot$ with **LS220 + pions**.

Figure 1, *b* shows the same setting, but with EoS **LS220 + hyperons**. Note the change in the axis scales: the collapse occurs faster at higher densities and the EoS is much softer: the protoneutron star baryon mass at black hole collapse is $M_B = 2M_\odot$. Hyperons seem to have a strong influence on the collapse, and their fraction at the onset of black hole collapse is $Y_\Lambda = 0.41$. The sudden increase in the central density around $t = 70$ ms can be interpreted as a phase transition to hyperonic matter, which occurs for this progenitor with a high accretion rate. The protoneutron star oscillates after this phase transition, which may be seen in gravitational waves, for nonspherical models*. Contrary to the work by Sagert et al. [12], this phase transition does not seem to induce the launching of a second shock. Other types of stellar progenitors, with higher (solar-like) metallicities, do not exhibit a phase transition when collapsing to a black hole.

We have performed preliminary studies in 2D, with similar settings, except that for the stellar progenitor, a slow and differential rotation profile has been added. In these studies, the phase transition seems to be still present, although somehow smoothed. When looking at the gravitational waves, using the modified quadrupole formula, this phase transition has a clear imprint, with much more energy emitted, in particular, at higher frequencies than for the standard EoS **LS220**. This can easily be understood by the phase transition itself, and by the protoneutron star "ringing" after the phase transition (see Fig. 1, *b* in 1D). Thus,

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[*] There cannot be any gravitational wave emission in spherical symmetry.

detection of such a gravitational wave signal by ground-based interferometric detector, such as LIGO or Virgo, could give valuable information about a possible phase transition in nuclear matter.

CONCLUSIONS

We have performed simulations of stellar core collapse to a black hole using new EoSs, based on the Lattimer & Swesty [7] one, but with additional particles, as pions or Λ hyperons. The particularity of these EoSs is that they are almost compatible with recent observations of two-solar-mass neutron stars. Nevertheless, the addition of new particle to these EoSs softens the protoneutron star, which then collapses more rapidly and, in the case of hyperons, may undergo a phase transition to hyperonic matter, in the case where the accretion from the progenitor is very high.

Axisymmetric studies show that the phase transition should be softened in multidimensional simulations, which might be a generic behavior, linked with the hydrodynamic properties (e.g., turbulence) of the flow. If this is the case, other studies producing phase transitions (e.g., to quark–gluon plasma, as in Sagert et al. [12]) might need to be considered with less symmetry assumptions, to see if the launching of a second shock can still occur without the spherical symmetry assumption. Additionally, 2D (or 3D) simulations can allow for the extraction of gravitational waves from the space-time, which can give observable predictions for these phenomena or, reversely, the observation of imprints of phase transition on the gravitational waves observed from a core collapse would be of extraordinary importance for nuclear physics.

However, the studies presented here are very preliminary and crude. Many improvements need to be done to confirm these behaviors, as a much better resolution in 2D (with a parallel version of the code) or a less simplified neutrino transport (see, e.g., Peres et al. [11]).

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