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SPH simulations of the induced gravitational collapse

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In the induced gravitational collapse (IGC) paradigm, a carbon–oxygen (CO) star collapses and explodes in a supernova (SN) in the presence of a binary companion, a neutron star (NS). The material ejected in the explosion is gravitationally attracted by the NS, triggering a hypercritical accretion process onto it. For compact systems, the accretion rate could be high enough for the NS to reach its critical mass, collapse in a black hole (BH) and emit an energetic (energy release $\gtrsim 10^{52}$ erg) gamma-ray burst (GRB). With the aim to identify the separatrix of systems in which a BH is formed and characterize the observational signatures of the above process, we have performed three-dimensional (3D) smoothed-particle-hydrodynamics (SPH) numerical simulations of the SN expansion in the presence of the NS companion and the evolution of the NS during the accretion process. We here summarize the results of the above simulations for a wide range of the initial conditions of the parameter space.

Keywords: Gamma-ray burst – supernovae – binaries

1 Introduction

Gamma ray bursts (GRBs) are the brightest explosions in the universe with isotropic luminosity between 10^{47}–10^{54} erg s^{-1}. Since its first detection in the late 1960s by the

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Vella Satellites [1], many efforts have been made in order to enrich the understanding of these phenomena. The theory has advanced with the new knowledge given by all the observational campaigns done until now. For example, with BATSE, as part of the Compton Gamma-ray Observatory (CGRO) launched in 1991, it was evidenced that GRBs follow an isotropic distribution in the sky [2]; Beppo-SAX, put in orbit in 1996, detected the first GRB afterglow, making it possible to determine their cosmological origin in star formation regions of galaxies [3, 4]. The relation between GRBs and SNe was discovered first with the detection of GRB 980425 associated with the broad-line type Ic SN 1998bw [5], and the first truly solid evidence came with the detection of GRB 030329 ($z = 0.1685$ [6]) with SN 2003dh [7].

Many models have been proposed as progenitors of long GRBs. The most popular among the scientific community are the *magnetar* [8] and the *collapsar* models [9, 10]. In the former, the energy source for GRBs comes from the spindown of a newly formed highly magnetized rotating NS with an initial period of about one millisecond [11]. While in the latter, the iron core of a rapidly rotating massive star ($M > 20\,M_{\odot}$) collapses to a black hole (BH), either directly or during the accretion phase that follows the core collapse, and a massive accretion disk is formed around it.

In this contribution, we focus on the IGC model introduced as an alternative progenitor of the subfamily of GRBs with energies $E_{\rm iso} \gtrsim 10^{52}$ erg associated with type Ic SN [12, 13, 14]. The IGC model considers that the long GRBs associated with type Ic SNe originate in binary systems. The progenitor is a carbon–oxygen (CO) star with a neutron star (NS) companion. The CO star collapses, leaving a new NS (νNS), and explodes leading to a SN explosion. Part of the material ejected in the SN is captured gravitationally by the NS companion, triggering an hypercritical accretion on it. At the same time, part of the material at the innermost layers of the SN ejecta, fallback onto the νNS. Depending, mainly, on the initial binary separation, this scenario leads to different outcomes. When the accretion rate onto the NS is high enough (for short binary separation), the NS can reach its critical mass and collapse to a BH. We have called this system binary-driven hypernova (BdHN) of type I. A BdHN of type II (a less energetic event) happens when the accretion does not lead the NS to gravitational collapse. If, after the SN explosion, the system remains gravitationally bound, BdHNe I produce BH–NS binaries, while BdHNe II produce NS–NS binaries.

In the following, we will present the results of 3D SPH numerical simulations of the expansion of the SN ejecta under the effect of the gravitational field of the νNS and the NS companion. Then, we will identify the initial parameter space (SN energy, initial NS mass, initial binary period), in which it is highly probable that one of the stars could accrete enough mass for it to collapse to a BH. Finally, we present how from the GRB observational data, we could constrain the initial binary parameters.

2 3D SPH simulations

We have adapted the SNSPH code [15] to model the IGC scenario (see [16] for details). Specifically, we have modeled the expansion of the SN ejecta under the effects of the νNS and the NS companion gravitational field. The two NSs are modeled as point particles that can interact gravitationally with the others SPH particles, but

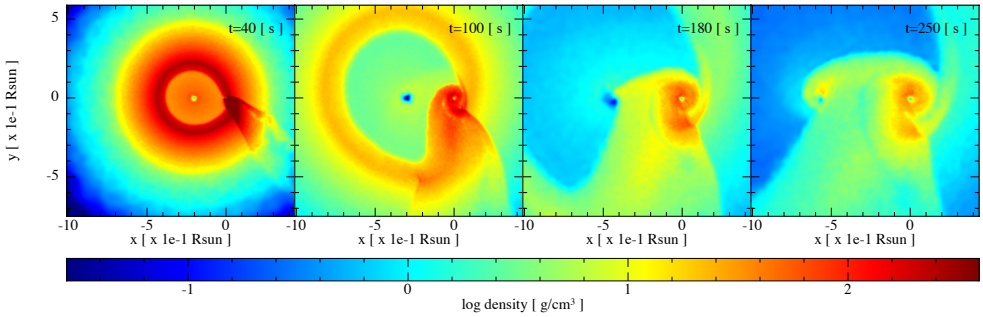


Figure 1 Density snapshots of the SN material at the equatorial plane of the binary system. At the center of each snapshot, it is the NS companion, while the νNS is at the left of it. This figure is taken from [16] with the kind permission of the authors.

not hydrodynamically. Additionally, these two point particles can also accrete other particles, if they fulfill the following conditions:

- They are inside the accretion radius.
- They are gravitationally bound to the point particle.
- Their angular momentum is larger than the angular momentum they should have if they would be rotating in a Keplerian orbit at the capture radius.

When any particle fulfills these conditions, it is removed from the simulation and its mass, linear and angular momentum are added to the point particle in order to conserve these quantities along the simulation.

The SPH simulations start at the SN breakout (i.e. when the SN shock radius reaches the CO star radius). First, we modeled the collapse and explosion of a main-sequence star with a one-dimensional code [17], and mapped its outcome to a 3D-SPH configuration. Figure 1 shows snapshots of the mass density at the binary equatorial plane at different times (see [16] for further details and views of the binary). At the beginning, the SN expansion is spherical, but when the particles approach the NS companion, they are gravitationally attracted. The particles initially form a kind of tail behind the NS companion, but at some point circularize around it, forming a kind of thick disk. At the same time, the innermost particles of the SN fallback onto the νNS. Later, the material that was captured in the disk by the NS companion is attracted by the νNS, forming also a disk around it.

Figure 2 shows the accretion rate on the νNS and the NS companion. For both stars, the accretion rate is of the order of $10^{-3} M_\odot$ s^{-1}, which is much larger than the Eddington's limit. These high accretion rates are possible because the NS surfaces forms on top a hot and high density atmosphere where the emission of neutrinos becomes highly efficient, taking away the gravitational energy of the accreted matter [18]. From Figure 2, we can see that the accretion rate on the νNS is dominated at earlier times by the accretion of the material during fallback, while at later times, the accretion rate bumps, corresponding to the accretion of the material from the NS companion. This is a unique feature of BdHNe with respect to the fallback accretion in the SN explosion of a single star.

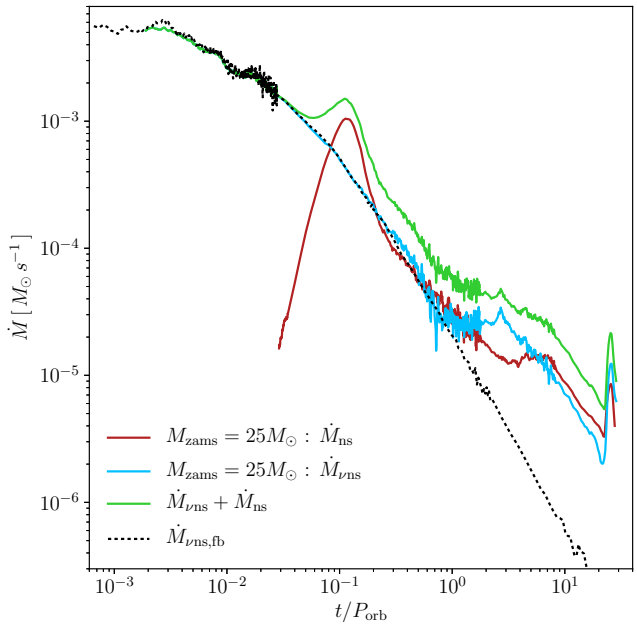


Figure 2 Accretion rate on the NS companion (in red) and the νNS (in blue) along the simulation. This figure is taken from [16] with the kind permission of the authors.

We now describe the principal consequences when the initial condition of the simulations are changed:

- **SN kinetic energy.** If we reduce the kinetic energy of the particles of the SN, we find that the maximum accretion rate amplitude on the NS companion remains about the same order ($\sim 10^{-3} M_\odot$ s^{-1}) but the shape of the accretion rate changes. It becomes flatter, so the star accretes at high accretion rates for a longer time, leaving a more massive final star. On the other hand, the earlier accretion rate on the νNS companion does not change with the SN energy (i.e. the fallback accretion remains nearly the same in all the cases), but the second bump happens earlier and is stronger for less energetic SN.
- **Initial binary period.** We have found a self-similar behavior of the accretion rate on the NS companion when the initial binary period of the CO–NS system increases. Namely, the shape of the accretion rate is more or less the same but its amplitude decreases for longer binary periods (longer binary separation). We also found that the initial fallback accretion onto the νNS companion does not change with the binary period, but the amplitude of the second bump decreases when the binary period increases. For a much longer binary period, this bump disappears, as expected from the fallback accretion in the SN explosion of a single star.
- **NS initial mass**. The initial mass of the NS companion is not a very relevant parameter in the simulations. However, it obviously affects the time the star takes to become unstable and collapse to a BH.

3 Evolution of the NS companion and the νNS

The evolution of the NS gravitational mass is given by

$$\dot{M}_{\rm ns} = \left(\frac{\partial M_{\rm ns}}{\partial M_b}\right)_{J_{\rm ns}} \dot{M}_b + \left(\frac{\partial M_{\rm ns}}{\partial J_{\rm ns}}\right)_{M_b} \dot{J}_{\rm ns} \tag{1}$$

where $M_{\rm ns}$ is the gravitational mass of the NS, M_b is its baryonic mass and $J_{\rm ns}$ is its angular momentum. As a first approximation, we assume that the NS evolves from an equilibrium configuration to the next one and use the uniformly rotating NS equilibrium configurations of [19, 20]. These configurations were constructed using the public code RNS [21] to solve the axisymmetric Einstein equations for rotating NSs, for three selected relativistic mean-field nuclear matter (EOS) models: NL3, GM1 and TM1.

We see in the simulations that a kind of disk forms around the NS. Before the particles are actually accreted, they circularize and lose angular momentum owing to the friction force developed in the disk. Then, we need to integrate equation (1) assuming that disk accretion torque drives the stellar angular momentum evolution, i.e.,

$$\dot{J}_{\rm ns} = \chi l(R_d)\dot{M}_b, \tag{2}$$

where $l(R_d)$ is the specific (i.e., per unit mass) angular momentum of the particles orbiting at the last stable (circular) orbit around the rotating NS. We have introduced

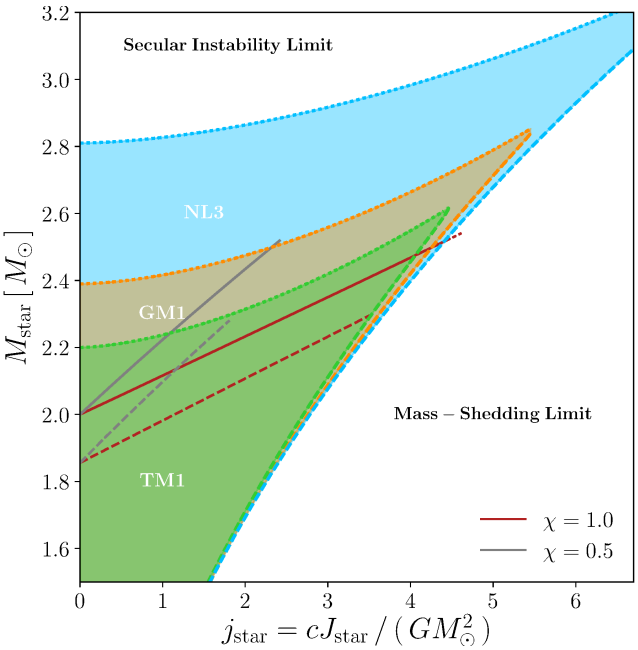


Figure 3 Evolution of the NS companion (solid line) and the νNS (dashed line) on the M-j plane during the accretion process.

a χ scale parameter that accounts for any angular momentum losses. The NS can accrete mass until it reaches an instability limit: the mass-shedding (Keplerian) limit or the secular axisymmetric instability.

Figure 3 shows the evolution of the νNS and the NS companion in the $M_{\rm star}$-$j_{\rm star}$ plane, where $j \equiv cJ_{\rm star}/(GM_{\odot}^2)$, during the accretion process. In this case, we have integrated equation (1) with equation (2), assuming that the particle mass sums to the star baryonic mass and the disk viscous timescale is shorter than the accretion timescale, i.e., we used the mass accretion rate obtained from the SPH simulations. When we assume that all the angular momentum from the last stable orbit is accreted by the star, it reaches quickly the mass-shedding limit. This means that matter at the equatorial surface of the star rotates with the local Keplerian frequency. This limit is almost independent of the EOS that describes the NS matter [19]. On the other hand, if there is some angular momentum loss, the NS companion and the νNS can reach the secular instability limit, where the star is unstable to non-axially symmetric perturbations. This limit depends on the nuclear EOS [19].

4 Conclusions

We described the 3D SPH numerical simulations of the IGC scenario with the SNSPH code. The fate of the CO–NS binary was explored for a wide parameter space including different CO star masses, orbital periods and SN explosion energies. Additionally, we have determined the conditions under which the NS gravitational collapse to a BH is possible.

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