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ON THE INDUCED GRAVITATIONAL COLLAPSE OF A NEUTRON STAR TO A BLACK HOLE BY A TYPE Ib/c SUPERNOVA

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ABSTRACT

It is understood that the supernovae (SNe) associated with gamma-ray bursts (GRBs) are of Type Ib/c. The temporal coincidence of the GRB and the SN continues to represent a major enigma of Relativistic Astrophysics. We elaborate here, from the earlier paradigm, that the concept of induced gravitational collapse is essential to explain the GRB–SN connection. The specific case of a close (orbital period $<$1 hr) binary system composed of an evolved star with a neutron star (NS) companion is considered. We evaluate the accretion rate onto the NS of the material expelled from the explosion of the core progenitor as a Type Ib/c SN and give the explicit expression of the accreted mass as a function of the nature of the components and binary parameters. We show that the NS can reach, in a few seconds, critical mass and consequently gravitationally collapse to a black hole. This gravitational collapse process leads to the emission of the GRB.

Key words: accretion, accretion disks – binaries: close – gamma-ray burst: general – stars: neutron

Online-only material: color figure

The systematic and spectroscopic analysis of gamma-ray burst (GRB)–supernova (SN) events, following the pioneering discovery of the temporal coincidence of GRB 980425 (Pian et al. 2000) and SN 1998bw (Galama et al. 1998), has given evidence for the association of other nearby GRBs with Type Ib/c SNe (see, e.g., Della Valle 2011; Hjorth & Bloom 2011, for a recent review on GRB–SN systems). It also has been clearly understood that the most likely explanation for SN Ib/c, which lack hydrogen (H)/helium (He) in their spectra, is that the SN core progenitor star, likely a He, CO, or a Wolf–Rayet star, is in a binary system with a compact companion, a neutron star (NS; see, e.g., Nomoto & Hashimoto 1988; Iwamoto et al. 1994 and Fryer et al. 2007; Yoon et al. 2010 for more recent calculations).

In the current literature, there have been attempts to explain both the SN and the GRB as two aspects of the same astrophysical phenomenon. Hence, GRBs have been assumed to originate from a specially violent SN process, a hypernova, or a collapsar (see, e.g., Woosley & Bloom 2006 and references therein). Both of these possibilities imply a very dense and strong wind-like CircumBurst Medium (CBM) structure. Such a dense medium appears to be in contrast with the CBM density found in most GRBs (see, e.g., Figure 10 in Izzo et al. 2012b). In fact, the average CBM density, inferred from the analysis of the afterglow, has been shown to be of the order of 1 particle cm^{-3} in most of the cases (see, e.g., Ruffini 2011). The only significant contribution to the baryonic matter component in the GRB process is the one represented by the baryon load (Ruffini et al. 2000). In a GRB, the electron–positron plasma, loaded with a certain amount of baryonic matter, is expected to expand at ultrarelativistic velocities with Lorentz factors $\Gamma \gtrsim 100$ (Shemi & Piran 1990; Piran et al. 1993; Meszaros et al. 1993). Such an ultrarelativistic expansion can actually occur if the amount of baryonic matter, quantifiable through the baryon load parameter, $B = M_B c^2/E_{e^+e^-}$, where M_B is the engulfed baryon mass from the progenitor remnant and $E_{e^+e^-}$ is the total energy of the e^+e^- plasma, does not exceed the critical value $B \sim 10^{-2}$ (see Ruffini et al. 2000 for details).

In our approach, we have assumed that the GRB consistently has to originate from the gravitational collapse to a black hole (BH). The SN instead follows the complex pattern of the final evolution of a massive star, possibly leading to a NS or to a complete explosion but never to a BH. There is a further general argument in favor of this explanation, namely, the extremely different energetics of SNe and GRBs. While the SN energy range is 10^{49}–10^{51} erg, the GRBs are in a larger and wider range of energies, 10^{49}–10^{54} erg. It is clear that in no way can a GRB, being energetically dominant, originate from the SN.

There are however scenarios for GRB–SN systems that invoke a single progenitor, e.g., the collapse of massive stars (see, e.g., Zhang 2011 for a recent review). In these models, the core of the star must rotate at very high rates in order to produce, during the gravitational collapse, a collimated (e.g., jet) emission with beaming angle θ_j. In this way, an event with observed isotropic energy $E_{\rm iso}$ corresponds to actual energy released at the source reduced by the beaming factor $f_b = (1-\cos\theta_j) \sim \theta_j^2/2 < 1$, namely, $E_s = f_b E_{\rm iso} < E_{\rm iso}$ (see Woosley & Bloom 2006; Zhang 2011 and references therein). Outstandingly, small beaming factors of order $f_p \sim 1/500$, corresponding to jet angles $\theta_j \sim 1^\circ$, are needed to bring the most energetic GRBS with $E_{\rm iso} \sim 10^{54}$ erg to standard energies $\sim 10^{51}$ erg (Frail et al. 2001). However, observational evidence of the existence of such narrow beaming angles in GRBs, as suggested by these models, is inconclusive (see, e.g., Covino et al. 2006; Sato et al. 2007; Burrows et al. 2009).

We explain the temporal coincidence of the two phenomena, the SN explosion and the GRB, within the concept of *induced gravitational collapse* (Ruffini et al. 2001, 2008). In recent years, we have outlined two different possible scenarios for the GRB–SN connection. In the first version (Ruffini et al. 2001), we have considered the possibility that the GRBs may have triggered the SN event. For this scenario to occur, the companion star had to be in a very special phase of its thermonuclear evolution (see Ruffini et al. 2001 for details).

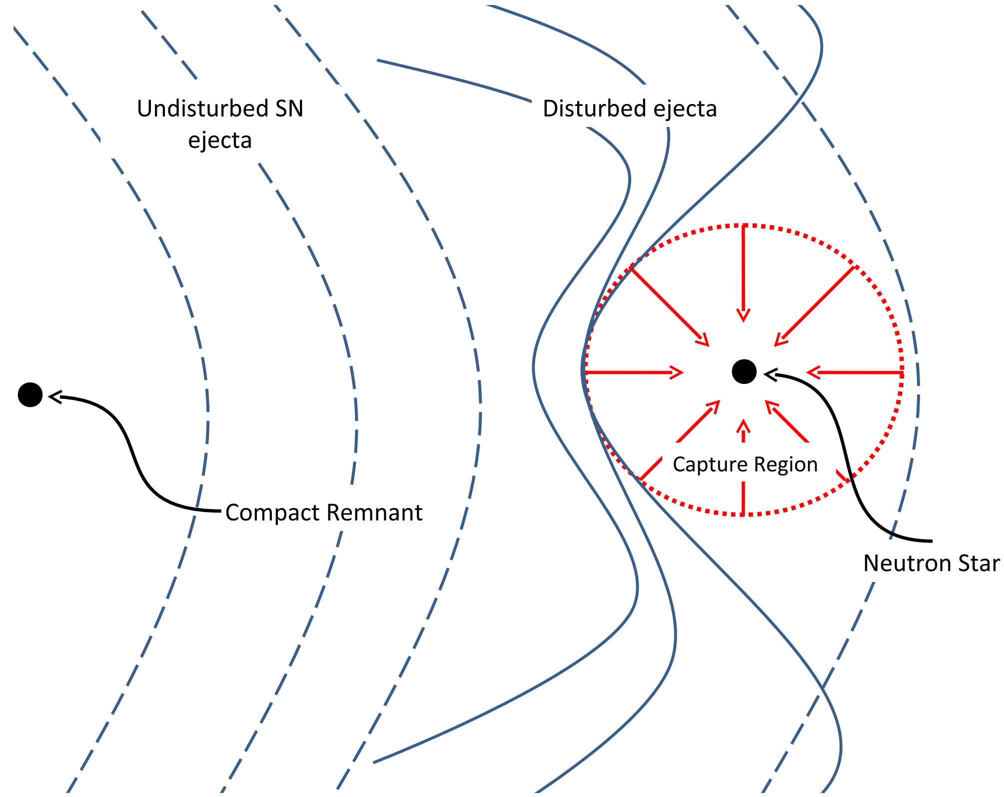

Figure 1. Sketch of the accretion induced collapse scenario. An evolved star in close binary with an NS explodes as an SN Ib/c. The NS rapidly accretes a part of the SN ejecta and reaches critical mass in a few seconds, undergoing gravitational collapse to a BH, emitting the GRB.

(A color version of this figure is available in the online journal.)

More recently, we have proposed (Ruffini et al. 2008) a different possibility occurring at the final stages of the evolution of a close binary system: the explosion in such system of a Ib/c SN leads to an accretion process onto the NS companion. The NS will reach the critical mass value, undergoing gravitational collapse to a BH. The process of gravitational collapse to a BH leads to the emission of the GRB (see Figure 1). In this Letter, we evaluate the accretion rate onto the NS and give the explicit expression of the accreted mass as a function of the nature of the components and the binary parameters.

We now turn to the details of the accretion process of the SN material onto the NS. In a spherically symmetric accretion process, the magnetospheric radius is given by (see e.g., Toropina et al. 2012) $R_m = B^2 R^6/(\dot{M}\sqrt{2GM_{\rm NS}})^{2/7}$, where B, $M_{\rm NS}$, and R are the NS magnetic field, mass, and radius, and $\dot{M} \equiv dM/dt$ is the mass accretion rate onto the NS. We now estimate the relative importance of the NS magnetic field on the accretion process. At the beginning of an SN explosion, the ejecta moves at high velocities $v \sim 10^9$ cm s^{-1}, and the NS will capture matter at a radius approximately given by $R^{\rm sph}_{\rm cap} \sim 2GM/v^2$. For $R_m \ll R^{\rm sph}_{\rm cap}$, we can neglect the effects of the magnetic field. In Figure 2, we have plotted the ratio between the magnetospheric radius and the gravitational capture radius as a function of the mass accretion rate onto an NS of $B = 10^{12}$ G, $M_{\rm NS} = 1.4\,M_\odot$, $R = 10^6$ cm, and for a flow with velocity $v = 10^9$ cm s^{-1}. It can be seen how for high accretion rates the influence of the magnetosphere is negligible.

We therefore assume hereafter, for simplicity, that the NS is non-rotating and neglect the effects of the magnetosphere. The NS captures the material ejected from the core collapse of the companion star in a region delimited by the radius $R_{\rm cap}$ from the NS center

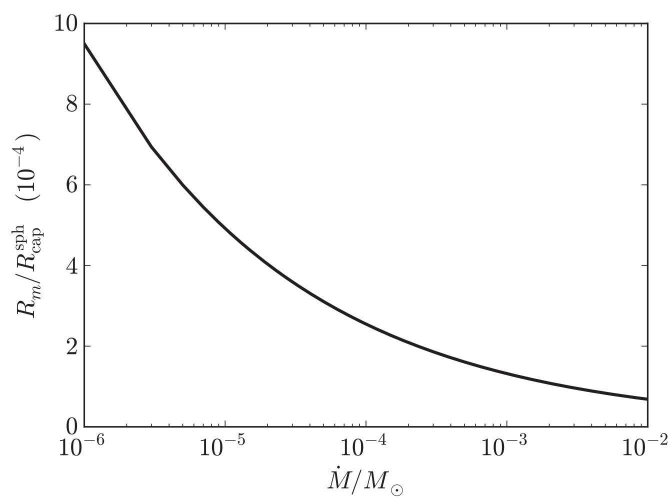

Figure 2. Magnetospheric to gravitational capture radius ratio of an NS of $B = 10^{12}$ G, $M_{\rm NS} = 1.4\,M_\odot$, $R = 10^6$ cm, in the spherically symmetric case. The flow velocity has been assumed to be $v = 10^9$ cm s^{-1}.

$$R_{\rm cap} = \frac{2GM_{\rm NS}}{v^2_{\rm rel,ej}}, \quad (1)$$

where $v_{\rm rel,ej}$ is the ejecta velocity relative to the orbital motion of the NS

$$v_{\rm rel,ej} = \sqrt{v^2_{\rm orb} + v^2_{\rm ej}}\,, \qquad v_{\rm orb} = \sqrt{\frac{G(M_{\rm SN-prog} + M_{\rm NS})}{a}}, \quad (2)$$

with $v_{\rm ej}$ the velocity of the ejecta and $v_{\rm orb}$ the orbital velocity of the NS, where a is the binary separation. Here, we have assumed that the velocity of the SN ejecta $v_{\rm ej}$ is much larger than the sound speed c_s of the material, namely, that the Mach number of the SN ejecta satisfies $\mathcal{M} = v_{\rm ej}/c_s \gg 1$, which is a reasonable approximation in the present case. The orbital period of the binary system is

$$P = \sqrt{\frac{4\pi^2 a^3}{G(M_{\rm SN-prog} + M_{\rm NS})}}, \tag{3}$$

where $M_{\rm SN-prog}$ is the mass of the SN core progenitor.

The NS accretes the material that enters into its capture region defined by Equation (1). The mass accretion rate is given by (see Bondi & Hoyle 1944 for details)

$$\dot{M} = \xi \pi \rho_{\rm ej} R_{\rm cap}^2 v_{ej} = \xi \pi \rho_{ej} \frac{(2GM_{\rm NS})^2}{\left(v_{\rm orb}^2 + v_{ej}^2\right)^{3/2}}, \tag{4}$$

where the parameter ξ is in the range $1/2 \leqslant \xi \leqslant 1$, $\rho_{\rm ej}$ is the density of the accreted material, and in the last equality we have used Equations (1) and (2). The upper value $\xi = 1$ corresponds to the Hoyle–Lyttleton accretion rate (Hoyle & Lyttleton 1939). The actual value of ξ depends on the properties of the medium in which the accretion process occurs, e.g., vacuum, wind. In Figure 1, we have sketched the accreting process of the SN ejected material onto the NS.

The density of the ejected material can be assumed to decrease in time following the simple power law (see, e.g., Chevalier 1989)

$$\rho_{\rm ej}(t) = \frac{3M_{\rm ej}(t)}{4\pi r_{\rm ej}^3(t)} = \frac{3M_{\rm ej}}{4\pi \sigma^3 t^{3n}}, \tag{5}$$

where, without loss of generality, we have assumed that the radius of the SN ejecta expands as $r_{\rm ej} = \sigma t^n$, with σ and n being constants. The velocity of the ejecta is thus $v_{\rm ej} = n r_{\rm ej}/t$.

If the accreted mass onto the NS is much smaller than the initial mass of the ejecta, i.e., $M_{\rm acc}(t)/M_{\rm ej}(0) \ll 1$, one can assume $M_{\rm ej}(t) \approx M_{\rm ej}(0)$ and thus the integration of Equation (4) gives

$$\Delta M(t) = \int_{t_0^{\rm acc}}^{t} \dot{M} dt = \pi \xi (2GM_{\rm NS})^2 \frac{3M_{\rm ej}(0)}{4\pi n^3 \sigma^6} \mathcal{F} \Big|_{t_0^{\rm acc}}^{t}, \tag{6}$$

where

$$\mathcal{F} = \frac{t^{-3(n+1)}\left[-4n(2n-1)t^{4n}\sqrt{kt^{2-2n}+1}\,{}_2F_1\left(\frac{1}{2}, \frac{1}{n-1}; \frac{n}{n-1}; -kt^{2-2n}\right) - k^2\left(n^2-1\right]t^4 + 2k(n-1)(2n-1)t^{2n+2} + 4n(2n-1)t^{4n}\right)}{k^3(n-1)(n+1)(3n-1)\sqrt{k+t^{2n-2}}}, \tag{7}$$

with $k = v_{\rm orb}^2/(n\sigma)^2$, ${}_2F_1(a, b; c; z)$ is the hypergeometric function, and $t_0^{\rm acc}$ is the time at which the accretion process starts, namely, the time at which the SN ejecta reaches the NS capture region (see Figure 1), i.e., so $\Delta M(t) = 0$ for $t \leqslant t_0^{\rm acc}$. The above expression increases its accuracy for massive NSs close to the critical value, since the amount of mass needed to reach the critical mass by accretion is much smaller than $M_{\rm ej}$. In general, the total accreted mass must be computed from the full numerical integration of Equation (4).

We now turn to the maximum stable mass of an NS. Non-rotating NS equilibrium configurations have been recently constructed by Belvedere et al. (2012) taking into account the strong, weak, electromagnetic, and gravitational interactions within general relativity. The equilibrium equations are given by the general relativistic Thomas–Fermi equations, coupled with the Einstein–Maxwell system of equations, the Einstein–Maxwell–Thomas–Fermi system of equations, which must be solved under the condition of global charge neutrality. The strong interactions between nucleons have been modeled through the exchange of virtual mesons (σ, ω, ρ) within the Relativistic Mean Field (RMF) model, in the version of Boguta & Bodmer (1977). These self-consistent equations supersede the traditional Tolman–Oppenheimer–Volkoff ones that impose the condition of local charge neutrality throughout the configuration.

The uncertainties in the behavior of the nuclear equation of state (EOS) at densities about and larger than the nuclear saturation density $n_{\rm nuc} \approx 0.16$ fm^{-3} lead to a variety of EOS with different nuclear parameters. A crucial parameter in this respect is the so-called nuclear symmetry energy, $E_{\rm sym} = d^2(\mathcal{E}/n_b)/d\delta^2|_{\delta=0,n_{\rm nuc}}$, where $\mathcal{E}$ is the nuclear matter energy density, and $\delta = (n_n - n_p)/n_b$ is the asymmetry parameter with n_n, n_p, $n_b = n_p + n_p$ the neutron, proton, and baryon densities; we refer to Tsang et al. (2012) for a recent review. The symmetry energy is relevant for the determination of the value and density dependence of the particle abundances (e.g., n_n/n_p ratio) in the NS interior (see, e.g., Müther et al. 1987; Kubis 2007; Sharma & Pal 2009; Hebeler et al. 2010; Loan et al. 2011). The differences in the behavior of $E_{\rm sym}(n)$ for different nuclear EOS models and parameterizations lead to a variety of NS mass–radius relations and consequently to different values of the NS critical mass $M_{\rm crit}$ and the corresponding radii (see, e.g., Gandolfi et al. 2012). We have plotted in Figure 3 the behavior of the nuclear symmetry energy for the RMF parameterizations used in Belvedere et al. (2012) in a wide range of baryon densities expanding from $n_b \sim 0.7 n_{\rm nuc}$ all the way up to high

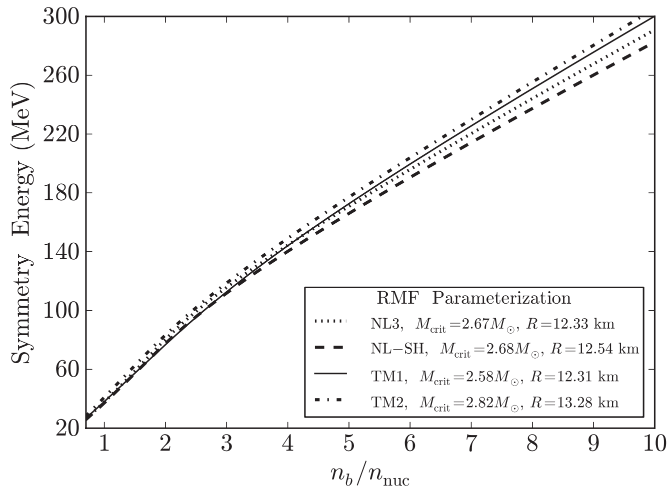

Figure 3. Nuclear symmetry energy as a function of the baryon density for selected parameterizations of the RMF nuclear model (see Belvedere et al. 2012 for details).

densities $n_b \sim 10n_{\rm nuc}$ found in the cores of NSs; we have included in the legend the values of the mass and radius of the critical NS configuration, $M_{\rm crit}$ and R. Concerning our induced gravitational collapse scenario, the precise value of the time needed for the NS to reach $M_{\rm crit}$ by accretion of the SN material depends, for fixed binary parameters ($M_{\rm NS}$, a, $M_{\rm prog}$, $v_{\rm ej}$), on the adopted EOS which leads to a specific value of $M_{\rm crit}$.

The high and rapid accretion rate of the SN material can lead to the NS mass reaching the critical value $M_{\rm crit}$. This system will undergo gravitational collapse to a BH, producing a GRB. The initial NS mass is likely to be rather high due to the highly non-conservative mass transfer during the previous history of the evolution of the binary system (see, e.g., Nomoto & Hashimoto 1988; Iwamoto et al. 1994, for details). Thus, the NS could reach critical mass in just a few seconds. Indeed, Equation (4) shows that for an ejecta density 10^6 g cm^{-3} and ejecta velocity 10^9 cm s^{-1}, the accretion rate might be as large as $\dot{M} \sim 0.1\, M_\odot$ s^{-1}.

The occurrence of a GRB–SN event in the scenario presented in this Letter is subjected to some specific conditions of the binary progenitor system, such as a short binary separation and orbital period $P < 1$ hr. This is indeed the case of GRB 090618 (Izzo et al. 2012b) and GRB 970828 (Izzo et al. 2012a), which we are going to analyze within the framework presented here in forthcoming publications. In addition to offering an explanation for the GRB–SN temporal coincidence, the considerations presented in this Letter leads to an astrophysical implementation of the concept of proto-BH, generically introduced in our previous works on of GRBs 090618, 970828, and 101023 (see Izzo et al. 2012b, 2012a; Penacchioni et al. 2012, respectively). The proto-BH represents the first stages, $20 \lesssim t \lesssim 200$ s, of the SN evolution.

It is also worth noting that the condition $B \lesssim 10^{-2}$ on the baryon load parameter of a GRB (Ruffini et al. 2000) might be a constraint on the binary separation a for the occurrence of a GRB–SN event. When the NS reaches critical mass, the distance between the location of the front of the undisturbed SN ejecta and the NS center should be $\ll a$, otherwise the emitted e^+e^- plasma in the GRB might engulf a large amount of baryonic matter from the SN ejecta, reaching or even overcoming the critical value $B \sim 10^{-2}$.

It is appropriate now to discuss the possible progenitors of such binary systems. A viable progenitor is represented by X-ray binaries such as Cen X-3 and Her X-1 (Schreier et al. 1972; Wilson 1972; Tananbaum et al. 1972; Leach & Ruffini 1973; Gursky & Ruffini 1975; Rawls et al. 2011). The binary system is expected to follow an evolutionary track (see Nomoto & Hashimoto 1988; Iwamoto et al. 1994, for details): the initial binary system is composed of main-sequence stars 1 and 2 with a mass ratio $M_2/M_1 \gtrsim 0.4$. The initial mass of star 1 is likely $M_1 \gtrsim 11\, M_\odot$, leaving a NS through a core-collapse event. Star 2, now with $M_2 \gtrsim 11\, M_\odot$ after some almost conservative mass transfer, evolves filling its Roche lobe. It then starts the spiraling in of the NS into the envelope of star 2. If the binary system does not merge, it will be composed of a helium star and a NS in close orbit. The helium star expands filling its Roche Lobe and a non-conservative mass transfer to the NS takes place. This scenario naturally leads to a binary system composed of a CO star and a massive NS, such as the one considered in this Letter.

We point out that the systems presenting a temporal coincidence of GRB–SN form a special class of GRBs.

1. There exist Ib/c SNe not associated with a GRB, e.g., the observations of SN 1994I (Immler et al. 2002) and SN 2002ap (Soria et al. 2004). Also, this class of apparently isolated SNe may be in a binary system with a NS companion at a large binary separation a and long orbital period P (3), and therefore the accretion rate (4) is not high enough to trigger the process of gravitational collapse of the NS. A new NS binary system may then be formed and lead to the emission of a short GRB in a NS merger after the shrinking of the binary orbit due to the emission of gravitational waves.
2. There are GRBs that do not show the presence of an associated SN. This is certainly the case for GRBs at large cosmological distances $z \gtrsim 0.6$ when the SN is not detectable even with the current high power optical telescopes. This is likely the case for GRB 101023 (Penacchioni et al. 2012).
3. There is the most interesting case of GRBs that do not show an SN, although it should be detectable. This is the case of GRB 060614 (Caito et al. 2009) in which a possible progenitor has been indicated in a binary system formed of a white dwarf and a NS, which clearly departs from the binary class considered in this Letter. Finally, there are systems emitting genuinely short GRBs that have been proven to have their progenitors in binary NSs, and clearly do not have an associated SN, e.g., GRB 090227B (Muccino et al. 2012; Rueda & Ruffini 2012).

Before closing, we like to look to the problem of the remnants of the class of GRBs considered in this Letter. It is clear that after the occurrence of the SN and the GRB emission, the outcome is represented, respectively, by an NS and a BH. A possible strong evidence of the NS formation is represented by the observation of a characteristic late ($t = 10^8$–10^9 s) X-ray emission (called URCA sources; see Ruffini et al. 2005) that has been interpreted to have originated from young ($t \sim 1$ minute (10–100) years), hot ($T \sim 10^7$–10^8 K) NS, which we have called neo-NS (see Negreiros et al. 2012 for details). This has been indeed observed in GRB 090618 (Izzo et al. 2012b) and also in GRB 101023 (Penacchioni et al. 2012). If the NS and the BH are gravitationally bound they give rise to a new kind of binary system, which can lead itself to the merging of the NS and the BH and consequently to a new process of gravitational collapse of the NS into the BH. In this case the system could indicate yet another process of GRB emission and possibly a predominant emission in gravitational waves.

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