X, Gamma-Rays, and Gravitational Waves Emission in a Short Gamma-Ray Burst

F.G. Oliveira, Jorge A. Rueda, and R. Ruffini

Abstract The recent progress in the understanding the physical nature of neutron stars (NSs) and the first observational evidence of a genuinely short gamma-ray burst (GRB), GRB 090227B, allow to give an estimate of the gravitational waves versus the X and gamma-rays emission in a short GRB. NS binaries represent good candidates for the detection of gravitational waves emitted during the spiraling-in and final merging phase of the system that leads to the short GRB emission. The data analysis of the GRB 090227B by Muccino et al. (2013) have been shown to be consistent with a NS binary progenitor with masses $M_1 = M_2 = 1.34\,M_\odot$, radii $R_1 = R_2 = 12.2$ km, and a crust thickness $\Delta r \approx 0.47$ km, obtained from the new mass-radius relation by Belvedere et al. (2012) of NSs fulfilling global charge neutrality. Muccino et al. (2013) estimated that GRB 090227B is located at redshift $z \approx 1.6$, corresponding to a luminosity distance $d_L \approx 12.2$ Gpc. We assess the detectability of this source by the Advanced LIGO interferometer computing the signal-to-noise ratio (SNR) averaged over all polarizations and possible positions of the source with respect to the interferometer. We simulate the dynamics of the binary up to the contact point using the effective one-body formalism (EOB) in the fourth post-Newtonian approximation. We find that the gravitational waves signal would have been produced an SNR = 0.32 for a redshift $z = 1.61$. We find that, instead, this GRB would have been detected with an SNR = 8 if it would have been located at a redshift $z \approx 0.05$, or $d_L \approx 200$ Mpc.

1 Introduction

The connection between short GRB and gravitational waves signals as a coincidence of the same event would allow in principle to understand more about the origin of short GRBs (Kobayashi and Meszaros 2003). The first observational evidence of a genuinely short GRB, GRB 090227B (Muccino et al. 2013), offers the possibility of making the first joint analysis of the electromagnetic (X and gamma-rays) and

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gravitational waves emission in a short GRB. Genuine short GRBs have been theoretically predicted by the Fireshell model (Ruffini et al. 2001, 2002) as bursts with the same inner engine as the long bursts but endowed with a severely low value of the baryon load $B = M_B c^2/E^{tot}_{e+e-} \lesssim 10^{-5}$, where M_B is the mass of the baryons engulfed by the expanding ultrarelativistic e^+e^- plasma with total energy E^{tot}_{e+e-}. The emission from short GRBs mainly consists in a first emission, the proper GRB (P-GRB), followed by a softer emission squeezed on the first one. The typical separation between the two components in the lightcurve is expected to be shorter than 1–10 ms and therefore there is no afterglow emission from these sources.

It is widely accepted that the most likely progenitors of short GRBs, based on their observational features, are binary neutron star mergers. The emission of gravitational waves signals from such binary systems are the most expected signals to be detect by the interferometers called Advanced LIGO[1]-VIRGO[2] and they have been planned for to be operational in a few years with a improved sensitivity approximately a factor of 10 better than the first generation of detectors.

The time-resolved spectral analysis of the Fermi-GBM and Konus-Wind satellites data of GRB 090227B has led to an estimate of its baryon load of $B = (4.13 \pm 0.05) \times 10^{-5}$ (Muccino et al. 2013). The parameters inferred for GRB 090227B (see below) have led indeed to the identification of the progenitor of the genuine short GRB in a neutron star binary: (1) the natal kicks velocities imparted to a neutron star binary at birth can be even larger than 200 km s^{-1} and therefore a binary system can runaway to the halo of its host galaxy, clearly pointing to a very low average number density of the circumburst medium (CBM); (2) the very large total energy, which we can indeed infer in view of the absence of beaming, and the very short time scale of emission point again to a neutron star binary; (3) as we shall show the very small value of the baryon load is strikingly consistent with two neutron stars having small crusts, in line with the recent neutron star theory (Rotondo et al. 2011; Rueda et al. 2011; Belvedere et al. 2012).

The aim of this work is to give a brief review of the recent results (Oliveira et al. 2014) of the gravitational waves emission expected from GRB 090227B and how it compares and contrasts with the electromagnetic emission. In doing so the structure parameters of the neutron star components are determined and a comparison of the classic description of the orbital decay with respect to the dynamics accounting for general relativity corrections is also presented.

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[1] http://www.advancedligo.mit.edu.

[2] http://www.cascina.virgo.inft.it.

2 The Short GRB 090227B

We first recall that the canonical GRB within the Fireshell model has two components: an emission occurring at the transparency of the optically thick expanding e^+e^- baryon plasma (Ruffini et al. 2000), the Proper-GRB (P-GRB), followed by the extended afterglow, due to the interactions between the accelerated baryons and the CBM of average density $\langle n_{CBM} \rangle$. Such an extended afterglow comprises the prompt emission as well as the late phase of the afterglow (Bianco and Ruffini 2005a, b). The relative energy of these two components, for a given total energy of the plasma $E^{tot}_{e+e-} = E^{GRB}_{tot}$, where E^{GRB}_{tot} is the observed GRB energy, is uniquely a function of the above defined baryon load B.

According to the data analysis of GRB 090227B: $E^{GRB}_{tot} = 2.83 \times 10^{53}$, $B = 4.13 \times 10^{-5}$, the Lorentz factor at transparency is $\Gamma_{tr} = 1.44 \times 10^4$, the cosmological redshift is $z = 1.61$, the intrinsic duration of the GRB is $\Delta t = 0.35$, and $\langle n_{CBM} \rangle = 1.9 \times 10^{-5}$; we refer to Muccino et al. (2013) for further details. As we mentioned, an extremely low value of the baryon load, $B \lesssim 10^{-5}$ together with a low density of the CBM are imprints of a genuinely short GRB, in which no afterglow emission is observed. This is indeed the case of GRB 090227B.

The location of the binary in the very low interstellar density medium of galactic halos makes possible to probe the neutron star theory and equation of state (EoS) via the knowledge of the baryon load B inferred from the fitting of the GRB light curve and spectrum. For the modeling of the neutron star we follow (Belvedere et al. 2012) where configurations of equilibrium were computed satisfying the strong, weak, electromagnetic and gravitational interactions in a general relativistic framework and the condition of global charge neutrality, instead of the traditionally adopted ansatz of local charge neutrality, which have been shown to be incompatible with the equilibrium equations of motion (see Rotondo et al. 2011; Rueda et al. 2011, for further details).

For the nuclear EoS we use here the NL3, NL-SH, TM1 and TM2 models, which lead to critical masses and corresponding radii of globally neutral neutron stars: (2.67 $M_\odot$, $R = 12.33$ km; 2.68 $M_\odot$, $R = 12.54$ km; 2.58 $M_\odot$, $R = 12.31$ km; and 2.82 $M_\odot$, $R = 13.28$ km), respectively (Belvedere et al. 2012).

The baryonic matter which the GRB interact with is in these systems provided by the material of the neutron star crusts ejected during the binary coalescence. Thus, a theoretical expectation of the baryon load B left in a binary neutron star merger is $B_{\rm th} = \eta M_{\rm crust} c^2 / E^{GRB}_{tot}$, where η is the fraction of the crustal mass ejected. In Fig. 1 we have plotted $B_{\rm th}$ for GRB 090227B, namely using $E^{GRB}_{tot} = 2.83 \times 10^{53}$ erg, as a function of the mass M of the globally and locally neutral neutron stars (Belvedere et al. 2012).

The agreement of the observed baryon load of GRB 090227B with the low mass of the crust obtained from the globally neutral neutron stars of Belvedere et al. (2012) is evident. It can be compared and contrasted with the ones obtained enforcing the local charge neutrality condition. For the specific binary neutron star system adopted here we obtain a theoretical prediction of the baryon load with $\eta = 1$, $B_{\rm th} \sim 4.5 \times 10^{-4}$, or a mass of the baryons $M_B = E^B_{\rm crust}/c^2 \sim 7.2 \times 10^{-5}\, M_\odot$,

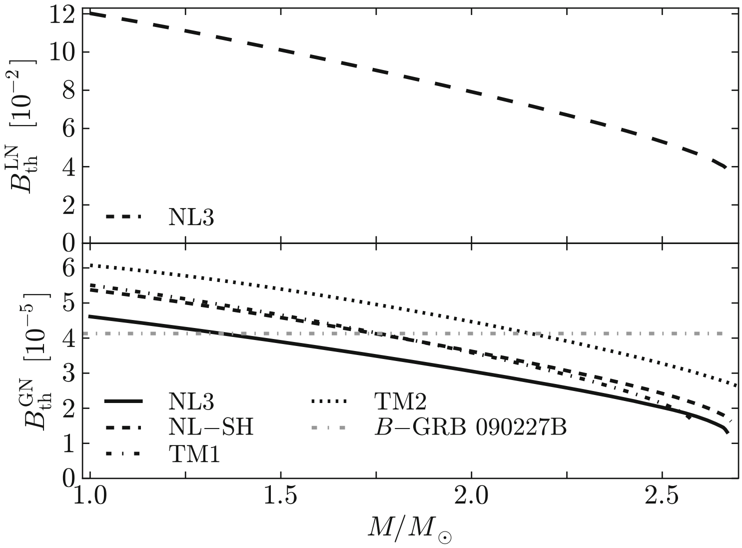

Fig. 1 Baryon load expected to be left by a binary neutron star merger, given by $B_{\rm th} = \eta M_{\rm crust}c^2/E_{tot}^{GRB}$ for $\eta = 1$, as a function of the total mass M of globally (*lower panel*, *solid black curve*, units 10^{-5}) and locally neutral (*upper panel*, *dashed black curve*, units 10^{-2}) neutron stars, for the case of GRB 090227B. We have indicated the observed baryon load of GRB 090227B, $B = 4.13 \times 10^{-5}$, with the *dotted-dashed gray horizontal* (Muccino et al. 2013)

to be confronted with the one obtained from the fitting procedure of GRB 090227B, $B \sim 4.13 \times 10^{-5}$, corresponding to $M_B = B \times E_{tot}^{GRB}/c^2 \sim 0.7 \times 10^{-5}\,{\rm M}_{\odot}$. A perfect agreement would require $\eta \approx 0.1$ for the NL3 nuclear model, while the other nuclear parameterizations require a slightly lower value of η. These theoretical predictions of the neutron star crust mass $M_{\rm crust}$ and the value of $E_{\rm crust}^{B}$ and $B_{\rm th}$ have been inferred for a crust with a density at its edge equal to the neutron drip density, $\rho_{\rm drip} \sim 4.3 \times 10^{11}$ g cm^{-3}. Neutron star crusts with densities lower than $\rho_{\rm drip}$ are predicted by the globally neutral neutron stars (Belvedere et al. 2012), and therefore there is still the possibility of having smaller values of the baryonic matter ejected in a binary process, and consequently to still shorter genuinely short GRBs.

3 Gravitational Wave Emission

We turn to the analysis of the binary dynamics. Classically, the loss of orbital binding energy by emission of gravitational waves from the binary in spiral phase is obtained for non-relativistic and point-like particles, and can be written as a function of the gravitational waves frequency f as Landau and Lifshitz (1980)

$$\frac{dE_b}{df} = -\frac{1}{3}(\pi G)^{2/3}\mathscr{M}^{5/3}f^{-1/3}, \tag{1}$$

where $\mathscr{M} = (M_1 M_2)^{3/5}/(M_1 + M_2)^{1/5}$ is the called chirp mass. From the above equation is already possible to estimate the characteristic amplitude of the gravitational waves, see below Eq. (6).

Now we briefly review how to obtain the gravitational waves energy spectrum, dE/df, through the effective one-body (EOB) dynamics (Buonanno and Damour 1999; Damour 2000; Damour and Nagar 2010). The EOB formalism maps the conservative dynamics of a binary system of non spinning objects onto the geodesic dynamics of one body of reduced mass $\mu = M_1 M_2/M$, with $M = M_1 + M_2$ the total binary mass. The effective metric is a modified Schwarzschild metric where the rescaled radial coordinate $r = c^2 r_{12}/(GM)$ has been introduced, with r_{12} the distance between the two stars. The radial potential is given by

$$A(u;\nu) = 1 - 2u + 2\nu u^3 + a_4 \nu u^4 + a_5 \nu u^5, \tag{2}$$

where $u = 1/r = GM/(c^2 r_{12})$, $\nu = M_1 M_2/(M_1 + M_2)^2$ is the symmetric mass ratio, with the values of the 3 and 4 post-Newtonian (PN)-level coefficients given by $a_4 = 94/3 - (41/32)\pi^2$ and $a_5(\nu) = a5^{c0} + \nu a5^{cl}$ see details in Bini and Damour (2013). We will denote to as P_n^m the Padè approximant of order (n, m), which when applied to $A(u;\nu)$ ensures the convergence of the solution near the merger point (Damour and Nagar 2009).

The EOB Hamiltonian is $H = Mc^2\sqrt{1 + 2\nu(\hat{H}_{\rm eff} - 1)}$, and effective Hamiltonian is described by $\hat{H}_{\rm eff}^2 = A(u) + p_\phi^2 B(u)$, where $B(u) = u^2 A(u)$ and the angular momentum for the circular orbit is given by $p_\phi^2 = -A'(u)/[u^2 A(u)]'$, where prime stands for derivative with respect to u.

We need to write $\hat{H}_{\rm eff}$ as a function of the orbital angular velocity Ω, or orbital frequency f. For this, we need to write the u-parameter as a function of Ω, or f, which is obtained from the angular Hamilton equation of motion in the circular case

$$GM\Omega(u) = \frac{1}{u}\frac{\partial H}{\partial p_\phi} = \frac{MA(u)p_\phi(u)u^2}{H\hat{H}_{\rm eff}}. \tag{3}$$

The binding energy as a function of the orbital frequency is

$$E_b(\Omega) = H - Mc^2 = Mc^2[\sqrt{1 + 2\nu(\hat{H}_{\rm eff} - 1)} - 1], \tag{4}$$

and the gravitational energy spectrum is obtained through the derivative $dE_b/d\Omega$. The signal-to-noise ratio (SNR) making an rms average over all the possible source orientations, positions, and wave polarizations is given by,

$$\langle \mathrm{SNR}^2 \rangle = \int_{f_{\rm min}}^{f_{\rm max}} df_d \frac{h_c^2(f_d)}{5 f_d^2 S_h^2(f_d)}, \tag{5}$$

where $S_h(f)$ is the strain noise spectral density (units $1/\sqrt{\text{Hz}}$) in the interferometer and we have introduced the characteristic gravitational waves amplitude, h_c, defined using the Fourier transform of the gravitational waveform $h(t)$, $h_c(f) = f|\tilde{h}(f)|$, and it is given by

$$h_c^2(f) = \frac{2(1+z)^2}{\pi^2 d_L^2}\frac{dE_b}{df}[(1+z)f_d]. \tag{6}$$

with z the cosmological redshift, $f_d = f/(1+z)$ the gravitational wave frequency at the detector, $f = \Omega/\pi$ the frequency in the source frame, Ω is the orbital frequency, the minimal bandwidth frequency of the detector is $f_{\rm min}$, and $f_{\rm max} = f_c/(1+z)$ is the maximal bandwidth frequency, where $f_c = \Omega_c/\pi$ is the binary contact frequency and d_L is the luminosity distance.

Summarizing, we have shown that the observations of the genuinely short GRB 090227B lead to crucial information on the binary neutron star progenitor. The data obtained from the electromagnetic spectrum allows to probe crucial aspects of the correct theory of neutron stars and their equation of state.

The baryon load parameter B obtained from the analysis of GRB 090227B, leads to a most remarkable agreement of the baryonic matter expected to be ejected in a neutron star binary merger and validate the choice of the parameters of the binary components, $M_1 = M_2 = 1.34\,{\rm M}_\odot$, and $R_1 = R_2 = 12.24\,$km. This represents a test of the actual neutron star parameters described by the recent developed self-consistent theory of neutron stars (Belvedere et al. 2012) that takes into account the strong, weak, electromagnetic and gravitational interactions within general relativity, and satisfying the condition of global charge neutrality.

We estimate the detectability of GRB 090227B by the Advanced LIGO interferometer, by computing the SNR integrated up to the contact point of the binary components, for the theoretically inferred cosmological redshift, $z = 1.61$ (Muccino et al. 2013); see Fig. 2. We find that at such a redshift, the gravitational waves signal would produce a $\langle \text{SNR}\rangle \approx 0.32$, a value lower than the one needed for a positive detection, $\langle \text{SNR}\rangle = 8$. We turn to estimate the redshift at which Advanced LIGO would detect this GRB with a $\langle \text{SNR}\rangle = 8$ we obtained $z \approx 0.05$ or a distance to the source $d_L \approx 200\,$Mpc. Unfortunately, in the last 40 years, no such a GRB has been observed.

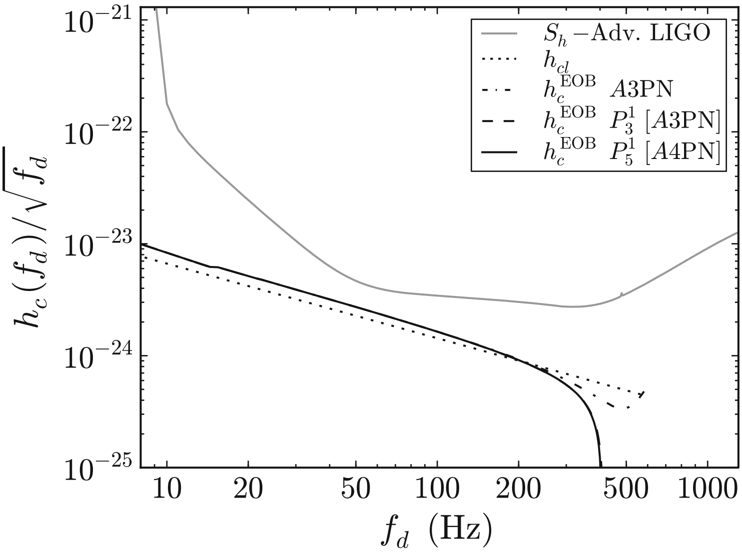

Fig. 2 Comparison of the characteristic gravitational waves amplitude per unit square frequency, $h_c(f_d)/\sqrt{f_d}$, see Eq. (6), with the noise density spectrum $S_h(f)$ of the Advanced LIGO interferometer. We use the binary neutron star parameters inferred for the short GRB 090227B, including the cosmological redshift $z = 1.61$. The comparison is made for both the dynamics given by the non-relativistic point-like particles approximation (*dotted black curve*) and the dynamics obtained from the EOB formalism. In the case of the EOB approach, the radial potential $A(u;\nu)$ was calculated using post-Newtonian approximation (PN). The *dotted-dashed black curve* is $A(u;\nu) = 3\,$PN, using the Padè approximant we calculated the $P_3^1[A(u;\nu) = 3\,\text{PN}]$ (*dashed black curve*) and the $P_5^1[A(u;\nu) = 4\,\text{PN}]$ (*solid black curve*). The noise spectral density of Advanced LIGO, $S_h(f)$, is represented by the *solid gray curve*

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