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Gravitational Waves Emission from the Short Gamma-Ray Burst 090227B

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The first observational evidence of a genuinely short gamma-ray burst, GRB 090227B, allows to give an estimate of the baryonic matter expelled in a neutron star merger as well as to estimate the gravitational waves versus the X and gamma-rays emission in a short GRB.

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1. Introduction

Short gamma-ray bursts (GRBs) are thought to be the result of binary neutron star (NS) mergers that overcome the critical mass of NSs and therefore gravitationally collapse to a black hole producing a very powerful emission in gamma-rays. Genuine short GRBs are theoretically predicted by the Fireshell model [3] 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 the total energy E^{tot}_{e+e-}. The aim of this work is to give a brief review of recent results [4] of the theoretically baryonic matter expected to be ejected in a NS binary merger and the total gravitational waves (GWs) energy expected from the analysis of GRB 090227B and how it compares and contrasts with the electromagnetic emission.

The data analysis of the light curve and spectrum of GRB 090227B gives the following GRB parameters [2]: $E^{GRB}_{tot} = E^{tot}_{e+e-} = 2.83 \times 10^{53}$ erg, $B = 4.13 \times 10^{-5}$, cosmological redshift $z = 1.61$, intrinsic duration of the GRB $\Delta t = 0.35$, and average density of the circumburst medium (CBM) $\langle n_{CBM} \rangle = 1.9 \times 10^{-5}$.

The baryonic matter which the GRB interacts with is in these systems provided by the material of the NS crusts ejected prior and during the binary coalescence. Thus, theoretical expectation of the baryon load B left in a binary NS merger is

$$B_{\rm th} = \eta \frac{M_{\rm crust} c^2}{E^{GRB}_{tot}} \quad (1)$$

where η is the fraction of the crustal mass ejected and $M_{\rm crust}$ is the sum of the crustal masses of the two neutron star binary components.

In Fig. 1 we have plotted the theoretical baryon load, as given by Eq. (1), for GRB 090227B as a function of the mass M of the neutron star. For the nuclear equation of state we use here the NL3 and TM1 models which lead to critical masses and corresponding radii of locally neutral and globally neutral neutron stars [1]: ($M^{\rm NL3,LN}_{\rm crit} = 2.80 M_\odot$, $R^{\rm NL3,LN}_{\rm crit} = 13.29$ km and $M^{\rm TM1,LN}_{\rm crit} = 2.21 M_\odot$, $R^{\rm TM1,LN}_{\rm crit} = 12.46$ km) and ($M^{\rm NL3,GN}_{\rm crit} = 2.67 M_\odot$, $R^{\rm NL3,GN}_{\rm crit} = 12.33$km and $M^{\rm TM1,GN}_{\rm crit} = 2.58 M_\odot$, $R^{\rm TM1,GN}_{\rm crit} = 12.31$km), respectively. For example, in the specific case of a symmetric binary NS system with components obeying global neutrality condition and the NL3 nuclear model ($M_1 = M_2 = M^{\rm NL3,GN}_{\rm crit}/2$), the theoretical prediction of the baryon load from Eq. (1), with $\eta = 0.1$, is $B_{\rm th} \sim 4.5 \times 10^{-5}$. This value is to be contrasted with that one obtained from the fitting procedure of GRB 090227B, $B \sim 4.13 \times 10^{-5}$. Clearly the baryon load parameter

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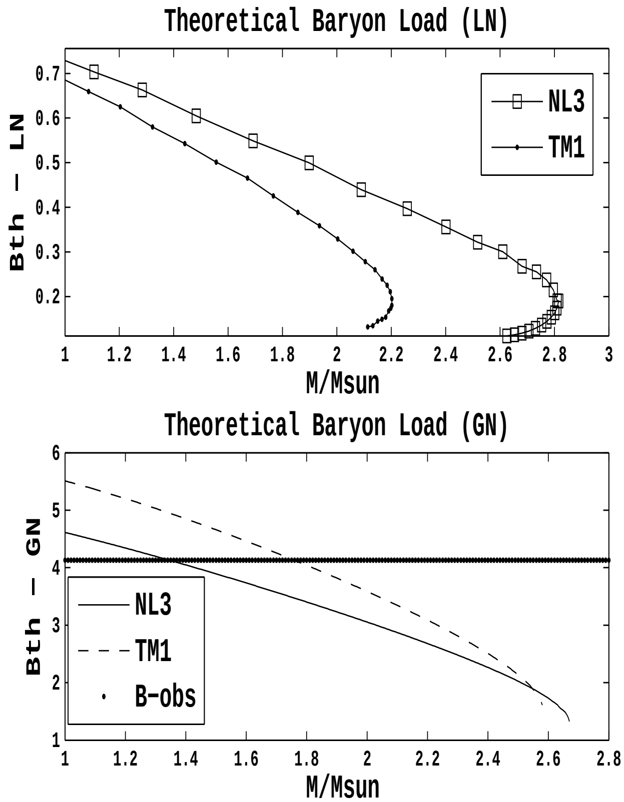

FIG. 1. Baryon load expected to be left by a binary NS merger, given by Eq. (1) for $\eta = 0.1$, as a function of the total mass M of globally (lower panel) and locally neutral (upper panel) neutron stars, for the case of GRB 090227B. We have indicated the observed baryon load of GRB 090227B, $B = 4.13$, with the dotted black horizontal [2].

B obtained from the analysis of GRB 090227B is in remarkable agreement with that expected from the baryonic matter ejected in a NS binary merger and validate the choice of the parameters of the binary components, $M_1 = M_2 \approx 1.34\ M_\odot$, and $R_1 = R_2 = 12.24$ km. This represents a test of the actual neutron stars parameters described by the recent developed theory of NSs [1] which takes into account the strong, weak, electromagnetic and gravitational interactions within general relativity and implements the condition of global but not local charge neutrality of the system.

Now we turn to estimate the energy released in gravitational waves using the effective one-body (EOB) formalism [5, 6]. The EOB Hamiltonian is given by $H = M\ c^2\sqrt{1 + 2\,\nu(\hat{H}_{\rm eff} - 1)}$ where $M = M_1 + M_2$ is the total binary mass, $\nu = \mu/M$ is the symmetric mass ratio, and the effective Hamiltonian is $\hat{H}^2_{\rm eff} = A(u) + p^2_\phi\, B(u)$. The angular momentum for the circular orbit is given by $p^2_\phi = -A'(u)/[u^2 A(u)]'$ where a prime stands for derivative with respect to $u = 1/r$ and $B(u) = u^2\ A(u)$, with the radial interaction potential $A(u)$ given by the expansion $\sim \nu a_n(\nu) u^n$, and each additional term is $(n-1)$-th post-Newtonian approximation. We will denote as P^m_n the Padè approximant of order (n, m), which when applied to $A(u;\nu)$ ensures the convergence of the solution near the merger point, see details in [8]. 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; we refer to Ref. [7] for details. The binding energy as a function of the orbital frequency is

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

The GW emission dominates the energy loss during the spiraling phase while the X and gamma-rays dominate from the coalescence with the final emission of the GRB. An absolute upper bound to the total energy emitted in the form of gravitational waves is obtained by integrating the loss of gravitational binding energy during the entire life of the binary from infinite separation all the way up to the merger point. For the NS binary discussed in this work we obtain $E_{\rm class} = 9.6 \times 10^{52}$ erg using the classical dynamics [9] and $E_{\rm EOB} = 7.42 \times 10^{52}$ erg for EOB dynamics. In the above estimate we have used the radial potential $P^1_5[A(u;\nu)]$ of the 4th order of the PN-coefficients; further details in [4].

We conclude that the GW energy emission, in the case of the genuinely GRB 090227B, is one order of magnitude lower than the emitted electromagnetic energy $E^{\rm GRB}_{\rm tot} = 2.83 \times 10^{53}$ erg.

We have also shown that the observations of the genuinely GRB 090227B lead to crucial information on the binary NS 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.

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