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GRB 140619B: a short GRB from a neutron star merger leading to the black hole formation

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We propose a classification into two families for short GRBs, both originating from the merging of binary neutron stars (NSs): family-1 with $E_{iso} < 10^{52}$ erg, leading to a very massive NS and representing the large majority of the observed short bursts, and family-2 with $E_{iso} > 10^{52}$ erg, leading to a black hole (BH). Following the prototype GRB 090227B, we present here a new example of family-2 short burst: GRB 140619B. From the spectral analysis of the early ~ 0.2 s, we infer an observed temperature of the e^+e^--plasma at transparency $kT = (324 \pm 33)$ keV, a theoretically derived redshift $z = 2.67 \pm 0.37$, a total burst energy $E^{tot}_{e^+e^-} = (6.03 \pm 0.79) \times 10^{52}$ erg, and a baryon load $B = (5.52 \pm 0.73) \times 10^{-5}$. We also estimate the corresponding emission of gravitational waves. The presence of the observed high energy emission ($\gtrsim 0.1$ GeV) is consistent with the accretion of $\approx 16\%$ of the NS–NS crustal masses onto the newly-formed BH. Depending on the amount of the total angular momentum of the merger, marked differences exist in the nature of the afterglows of these two families of short bursts. We also assert that both the families fulfill the recently proposed $E_{p,i}$–E_{iso} relation for short GRBs. The observed rate of such family-2 events is $\rho_0 = \left(2.6^{+4.1}_{-1.9}\right) \times 10^{-4}$ Gpc^{-3}yr^{-1}.

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1. Introduction

An ample literature indicates that short gamma-ray bursts (GRBs), with observed durations $T_{90} < 2$ s, originate from binary neutron star (NS) mergers (see [1], for a review). Recently we proposed a classification for short GRBs based on the total mass of the NS–NS merger, which can be smaller or larger than the NS critical mass ($M_{crit}^{NS} = 2.67$ M$_{\odot}$). Family-1 short bursts have $E_{iso} < 10^{52}$ erg and a total mass $< M_{crit}^{NS}$. The NSs coalescence leads to a massive NS and possibly a companion object, either a white dwarf or a less massive NS. Since no black hole (BH) is formed, no high energy emission is expected and, indeed, has not been observed, while ample emission in the X-ray and optical are observed [1], although without the regularity or nesting properties observed in family-2 long GRBs [2, 3]. Family-2 short bursts have $E_{iso} > 10^{52}$ erg and a total mass of the two NSs is $> M_{crit}^{NS}$. The merging leads to the BH formation and of some orbiting material or binary companion (see Fig. 1). For small values of the total angular momentum of the NS binary the formation of a single BH is expected and no X-ray, optical, and high-energy emission are observed; for larger values, some residual material and/or a binary companion is left orbiting and accreting onto the BH, leading to the presence of X-ray, optical, and high-energy emissions.

After the identification of GRB 090227B [4], we here present a second explicit example of a family-2 short burst: GRB 140619B. The redshift for both of these sources have been theoretically inferred by applying the fireshell model. A third example, GRB 090510, is only one with a measured redshift so far, e.g. $z = 0.903$. All of these family-2 short GRBs fulfill the $E_{p,i}$–E_{iso} relation discovered for family-1 short GRBs [5, 6]. Here $E_{p,i}$ is the rest-frame spectral peak energy.

In Sec. 2 we present our data analysis of GRB 140619B, from 8 keV up to 100 GeV. Then by applying the fireshell model to the observed data, we theoretically derive the redshift, $z = 2.67 \pm 0.37$, the burst energy, $E_{iso} > 10^{52}$ erg, and the value of the baryon load, $B \sim 10^{-5}$. We assume a symmetric NS–NS merger as the progenitor for GRB 140619B and discuss the possibility for Advanced LIGO to detect the emission of gravitational waves (GWs, see Sec. 2.2). In Sec. 2.3 we address the origin of the short-lived ($\Delta t \approx 5$ s) but significant 0.1–100 GeV emission. In Sec. 2.4 we give an estimate on the rate of such family-2 short GRBs. Finally we draw our conclusions.

2. Observations and data analysis

At 11:24:40.52 UT on 19th June 2014, the *Fermi*-GBM detector [7] triggered the short GRB 140619B. The on-ground calculated location was RA(J2000)= $08^h 54^m$ and Dec(J2000)= $-3^o 42'$ (5^o of statistical uncertainty), and was 32^o from the LAT boresight. The *Fermi*-LAT showed a significant increase in the event rate [8]. The burst was also detected by *Suzaku*-WAM [9]. No bright X-ray afterglow was detected by the *Swift*-XRT instrument in the field of view of the *Fermi* [10]. Therefore, no optical follow-up was possible and, thus, the redshift of the source is unknown.

We analyzed the GBM data (8 keV–40 MeV). In a first time interval, from T_0 to $T_0 + 0.192$ s (hereafter ΔT_1), we performed a spectral analysis considering the black body (BB) and Compt spectral models. The small difference in the C-STAT values listed in Tab. 1 suggests that both spectral models are equally viable. However, the α index of the Compt model is consistent with that of a BB within three σ, and the BB model has one parameter less than the Compt model. Therefore, we assumed the BB model as the best fit. In the second time interval, from $T_0 + 0.192$

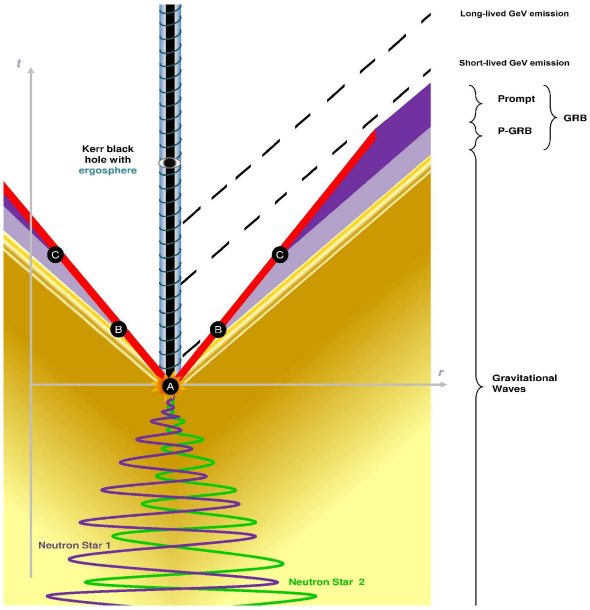

Figure 1: The space-time diagram of family-2 short GRBs. A) Vacuum polarization and self-acceleration of the fireshell; B) the transparency emission (P-GRB); C) interaction of the accelerated baryons with the local medium (prompt emission). The remnant of the merging is a Kerr BH. The accretion of a small (large) amount of orbiting matter onto the BH can give origin to the short (long) lived jetted 0.1–100 GeV.

ΔT	Model	K (ph keV^{-1} cm^{-2}s^{-1})	kT (MeV)	E_p (MeV)	α	F_{tot} (erg cm^{-2}s^{-1})	C-STAT/DOF
ΔT_1	Compt	$(6.3\pm2.0)\times10^{-3}$		1.60 ± 0.29	0.26 ± 0.32	$(9.4\pm1.6)\times10^{-6}$	318.92/346
	BB	$(7.5\pm2.2)\times10^{-8}$	0.32 ± 0.03			$(8.5\pm1.2)\times10^{-6}$	323.86/347
ΔT_2	Compt	$(7.2\pm1.4)\times10^{-3}$		1.28 ± 0.30	-0.11 ± 0.26	$(4.38\pm0.89)\times10^{-6}$	391.65/346
	BB	$(3.8\pm1.1)\times10^{-7}$	0.16 ± 0.02			$(2.33\pm0.28)\times10^{-6}$	392.23/347

Table 1: Spectral analyses in the ΔT_1 and ΔT_2 time intervals. Column content: the time interval ΔT, the spectral model, the model normalization K, the BB temperature kT, the peak energy E_p, the low-energy index α, the 8 keV–40 MeV energy flux F_{tot}, and the C-STAT value over the degrees of freedom (DOF).

s to $T_0 + 0.640$ s (hereafter ΔT_2), we considered again the Compt and BB spectral models (see Tab. 1). As discussed above, also in this case both models are equally probable. However, the BB model does not adequately fit the data at energies larger than 1 MeV. Therefore, we adopted the Compt model. More details on the spectral analysis can be found in Ref. [11].

We interpret the above data within the fireshell model of GRBs [12, 13, 14]. The ΔT_1 time interval, where the spectrum is consistent with a BB, represents the P-GRB, namely the emission at the transparency of the expanding e^+e^--photon-baryon plasma. The ΔT_2 time interval is identified with the prompt emission, a multi-wavelength emission due to the collisions between the accelerated baryons, after the transparency, and the circum-burst medium (CBM).

2.1 Redshift estimate and analysis of the prompt emission within fireshell model

The ratio between the P-GRB energy and total one can be estimated, independently to the redshift z, from the ratio of P-GRB and the total observed fluences, e.g. $S_{BB}/S_{tot} = (40.4\pm7.8)\%$ (see Tab. 1). Following the analysis described in Refs. [4, 11], from the above ratio, by applying

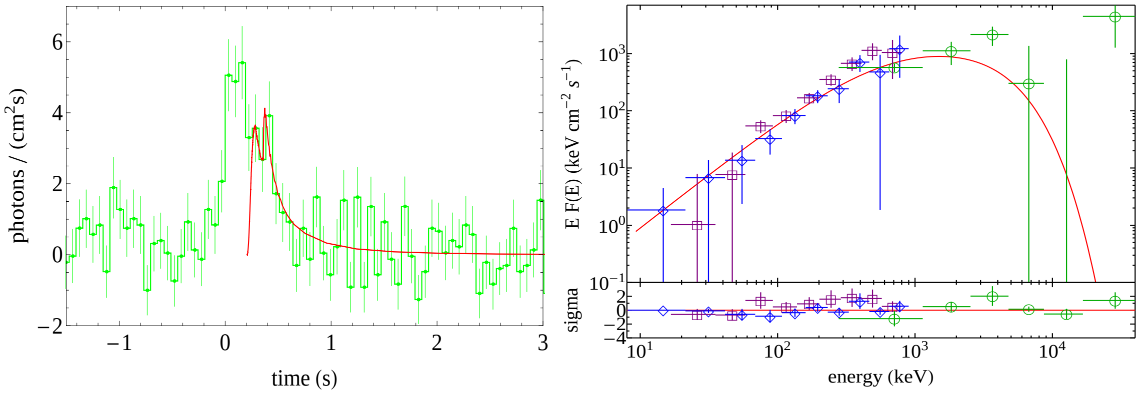

Figure 2: Left: the BGO-b1 (0.26–40 MeV) simulated light curve of the prompt emission of GRB 140619B. Right: comparison between the 8–900 keV data from the NaI-n6 (purple squares) and n9 (blue diamonds) detectors, and the 260 keV–40 MeV data from the BGO-b1 detector (green circles), and the simulation within the firshell model (solid red curve) in the time interval ΔT_2 (residuals are also shown).

the fireshell equations of motion, we obtained the redshift $z = 2.67 \pm 0.37$, the baryon load $B = (5.52 \pm 0.73) \times 10^{-5}$, and the total e^+e^- plasma energy $E^{tot}_{e^+e^-} = (6.03 \pm 0.79) \times 10^{52}$ ergs.

The BGO-b1 (0.26–40 MeV) prompt emission light curve in Fig. 2 (left panel) has been simulated by using a CBM number density distribution with an average value of $\langle n_{CBM} \rangle = (4.7 \pm 1.2) \times 10^{-5}$ cm^{-3}. The corresponding spectrum [15], is plotted in Fig. 2 (right panel).

2.2 The progenitor system and the GWs emission

We assume that the progenitor of GRB 140619B is a symmetric NS–NS merger and that the total crustal mass contributes to the GRB baryon load. For non-rotating NSs in the overall charge neutrality (OCN) treatment [16], the critical NS mass inferred from the NL3 nuclear model is $M^{NS}_{crit} = 2.67$ M$_\odot$. For NS masses $M_{NS} = 1.34$ M$_\odot$, so that $2M_{NS} > M^{NS}_{crit}$, the total NS crustal mass is $M_{2c} = 2M_c = 7.26 \times 10^{-5}$ M$_\odot$. The baryonic mass engulfed by the e^+e^- plasma is $M_B = E^{tot}_{e^+e^-} B/c^2 = (1.86 \pm 0.35) \times 10^{-6}$ M$_\odot$, therefore only $\approx 3\% M_{2c}$ contributes to the baryon load.

The GW emission from this binary NS gives a signal-to-noise ratio of $\langle \mathrm{SNR} \rangle \approx 0.5$, for an optimally located and polarized source with optimal face-on orbit, and it is lower than the optimal value SNR $= 8$ for detection by the Advanced LIGO interferometer[1]. The total gravitational radiation energy emitted during the entire inspiral-in phase all the way up to the merger, computed via the effective-one-body (EOB) formalism [17], is $E^T_{\mathrm{GW}} = 7.42 \times 10^{52}$ erg.

2.3 Considerations on the GeV emission of GRB 140619B

The spectrum of the observed short-lived emission (~ 5 s) at energies $\gtrsim 0.1$ GeV of GRB 140619B is best fitted by a power-law with a photon index $\gamma = -1.9$. Its isotropic energy is $E_{LAT} = (2.02 \pm 0.52) \times 10^{53}$ erg. By applying the pair production optical depth $\tau_{\gamma\gamma}$ formula [18], we obtained an average lower limit on the Lorentz factor, e.g. $\langle \Gamma_{LAT} \rangle = 110.5 \pm 4.4$. The emitted energy can be explained by the accretion onto the BH of a fraction of the residual crustal mass $M_{res} = 2M_c - M_B$, occurring at the innermost stable circular orbit of an extreme Kerr BH,

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

in the co-rotating case. In fact, assuming a jetted outflow, we have an accretion energy $E_{acc} = \eta_{acc}\eta_M M_{res}c^2 \lesssim E_{LAT}/(2\langle\Gamma_{LAT}\rangle^2)$, where η_{acc} is the accretion efficiency. From the above value of $\langle\Gamma_{LAT}\rangle$, the fraction of M_{res} which effectively accretes onto the BH is $\eta_M \lesssim (15.5\pm4.2)\%$.

2.4 The rate of family-2 short GRBs

Following Refs. [19, 20], with $N = 3$ family-2 short bursts, GRBs 090227B and 140619B with theoretically inferred redshifts and GRB 090510 with a measured one, we estimated their empirical rate $\rho_0 = (4\pi/\Omega_F)N/(V_{max}T_F)$, by evaluating for each source the maximum comoving volume V_{max} at which it would have been detected. Using the Fermi solid angle $\Omega_F \approx 9.6$ sr and observational period $T = 6$ years, we inferred $\rho_0 = \left(2.6^{+4.1}_{-1.9}\right) \times 10^{-4}\text{Gpc}^{-3}\text{yr}^{-1}$.

3. Conclusions

We here classified short GRBs into two families, both originating from NS–NS mergers, depending on the total NS masses $M_1 + M_2$, being $\gtrless M^{NS}_{crit}$. Family-1 short GRBs, with $E_{iso} < 10^{52}$ erg, we have $M_1 + M_2 < M^{NS}_{crit}$ and as a consequence no BH can be formed. Ample emission in the X-ray and optical are observed [1], although without any regularity or nesting properties, as observed in family-2 long GRBs [2, 3]. Family-2 short bursts, with $E_{iso} > 10^{52}$ erg, we have $M_1 + M_2 > M^{NS}_{crit}$ and a BH is formed. For small values of the total angular momentum we have the formation of a single BH; for larger values some residual matter orbits and accretes onto the BH. Within the second case we explained the short-lived 0.1–100 GeV emission of GRB 140619B as consistent with the accretion of $\approx 16\% M_{2c}$ onto an extreme Kerr BH, in the co-rotating case.

From our theoretical analysis, we inferred the astrophysical setting of GRB 140619B. 1) From the fit of the prompt emission light curve and spectrum, we derived a density $\langle n_{CBM}\rangle \approx 10^{-5}$ cm^{-3} typical of galactic halos where NS–NS mergers migrate [1]. 2) Assuming NS masses $M_1 = M_2 = 1.34$ M$_\odot$, the total energy emitted in gravitational waves corresponds to $E^T_{GW} = 7.42 \times 10^{52}$ erg; in view of the large z, the corresponding signal cannot be detected by the Advanded LIGO. 3) The empirical rate of family-2 short GRBs $\rho_0 = \left(2.6^{+4.1}_{-1.9}\right) \times 10^{-4}$ Gpc^{-3}yr^{-1}, represents clearly a lower limit in view of the difficulties in doing detailed time-resolved spectral analyses, necessary to identify their P-GRB emissions, and can be explained by the existing data of the galactic binary NSs. Their majority has $M_1 + M_2 < M^{NS}_{crit}$ and, therefore, they will lead to family-1 short bursts, whose rate is $\rho \approx 1$–10 Gpc^{-3}yr^{-1} [1]. The relative rates of family 1 and 2 short GRBs can lead, in principle, to an indirect determination of M^{NS}_{crit} (C. L. Fryer, private communication).

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