PROCEEDINGS OF SCIENCE

Binary progenitors of GRBs within the fireshell model

M. Enderli[∗†ab], **C. L. Bianco**[bc], **L. Izzo**[bc], **M. Kovačević**[†ab], **M. Muccino**[bc], **G. B. Pisani**[†ab], **J. A. Rueda**[bc], **R. Ruffini**[bc], **Y. Wang**[bc]
[a] *Université de Nice - Sophia Antipolis*
Cedex 2, Grand Château Parc Valrose, Nice, France
[b] *Dip. di fisica & ICRA, Sapienza Università di Roma*
P.le Aldo Moro 5, I-00185 Roma, Italy
[c] *ICRANet*
Piazza della Repubblica 10, I-65122, Pescara, Italy
E-mail: maxime.enderli@gmail.com

Recent results show that several distinct episodes may be individuated in some gamma-ray bursts (GRBs). Taking the effects of binarity into consideration - recalling in particular that type Ic supernovae (SNe) as well as most massive stars are indeed found in binary systems -, these results pave the way for a reinterpretation of GRBs as *composite events* in which binary interactions play a major role. It has been found that the observed diversity of GRBs may be accounted for by two main binary progenitor families: either a binary compact object merger, or the interaction between an evolved stellar core undergoing a SN and its companion neutron star. The energetics of a GRB is found to be largely determined by the presence or the absence of black hole formation. We present the different GRB families we obtain and we summarize their characteristics.

Swift: 10 Years of Discovery,
2-5 December 2014
La Sapienza University, Rome, Italy

∗Speaker.

†G.B. Pisani, M. Enderli, and M. Kovačević are supported by the Erasmus Mundus Joint Doctorate Program by Grant Numbers 2011-1640, 2012-1710, and 2013-1471 respectively, from the EACEA of the European Commission.

1. Introduction

It has been recognized for over 20 years that GRBs form (at least) two distinct groups, based on their duration and hardness properties [1, 2]. This dichotomy is thought to reveal an underlying difference in progenitor systems: long/soft GRBs are commonly interpreted as collapsar events, while circumstancial evidence points to a binary merger progenitor for short/hard bursts.

However, the fireshell model (reviewed e.g. in [3]) paints a different picture of the GRB phenomenon. In this framework, the collapse of an astronomical object to a black hole creates an overcritical electromagnetic field that powers the GRB through polarization of the vacuum. Indeed, the vacuum polarization leads to the production of an optically thick e^+/e^- pair plasma (the fireshell) that engulfs left-over baryons and expands and accelerates under its own pressure until it reaches transparency. A flash of thermal radiation, the Proper-GRB (P-GRB), is then emitted; the Lorentz factor of the plasma falls in the range $10^2 - 10^3$. Further interactions of the fireshell with the circumburst medium (CBM) produces the prompt emission.

Recent results (e.g. [4]) evidenced the fact that several episodes can be distinguished in a GRB. Since type Ic supernovae (those associated to GRBs) and massive stars are predominantly found in binary systems, it is a natural idea to study the consequences that binarity may have on a GRB event. It has been found that binary progenitors in the fireshell theory may be able to explain the diverse phenomenology of GRBs. A point of particular relevance is the presence or absence of black hole formation. The formation of a Kerr-Newman BH in the fireshell model may indeed deliver as much as $E_{iso} \sim 10^{55}$ erg for a 10 $M_\odot$ BH [5]. Whether a BH forms or not is therefore of great importance regarding the energetics of the event.

Observational tests of the model include in particular: discrimination between the P-GRB (for which a blackbody component is expected) and the prompt emission, as well as spectral identification of the different *episodes* (defined below) as done in [4]; observation of the X-ray afterglow that exhibits a standard behavior for the BdHN family defined below [6]; theoretical determination of redshifts that may be compared to redshift measurements (if available), as in [7].

2. The GRB - SN connection

GRB - SN coincidental occurences have been observed since 1998, with 35 spectroscopic or photometric associations up to the 31^{st} of May 2014 [8]. The Induced Gravitational Collapse (IGC) paradigm has been formulated to explain the GRB - SN connection [9, 10, 11]. It promotes the idea that the GRB and the SN do not have the same origin: an evolved stellar core reaching the end of its main sequence life undergoes a SN, but the GRB is a consequence of the triggered gravitational collapse of its companion neutron star. The IGC paradigm predicts four episodes, each of them being characterized by a number of observables [12].

An isotropic energy above $\sim 10^{52}$ erg is expected to be compatible with the formation of a black hole [12]. Less energetic GRBs can however still be linked to binary progenitors, if the configuration of the binary does not allow the companion NS to accrete enough matter to collapse. The critical distance between the two bodies is found to be of the order of 10^{11} cm. We therefore obtain two sub-families within the IGC formalism, termed *traditional hypernovae* with $E_{iso} \lesssim 10^{52}$ erg, and *binary driven hypernovae* (BdHN, [12] and references therein) with $E_{iso} \gtrsim 10^{52}$ erg.

PoS(SWIFT 10)073

2.1 Binary driven hypernovae (BdHNe)

A BdHN event may be identified through the detection and the characterization of its episodes. We refer to Fig. 1 (right panel) for a space-time diagram describing the sequence of events occuring in a BdHN (e.g. [12]). The **first episode** is due to hypercritical accretion of the SN ejecta onto the companion NS. The (non relativistic) emission is characterized by a spectrum that includes an evolving thermal component superimposed on a power law component. The computed radius of the blackbody emitter typically evolves from $\sim 10^9$ cm to $\sim 10^{10}$ cm. An episode 1 has been clearly observed in GRB 090618 [4] in particular. Its energetics may reach up to $\sim 10^{52}$ erg. **Episode 2** is the signature of the fireshell created by the collapse of the companion NS after it accreted enough matter to exceed its critical mass. Its distinctive features include an ultra-relativistic nature (with Lorentz factor $\Gamma \sim 10^2 - 10^3$) and a relatively hard peak energy $E_p > 100$ keV. The energetics of episode 2 may reach a few 10^{53} erg. **Episode 3**, starting at the end of episode 2 (that is, typically $\sim 10^2$s after trigger), is clearly visible in the X-ray domain. Its expansion velocity is only mildly relativistic. Three parts may be distinguished in the X-ray lightcurve: an initial steep decay, followed by a plateau phase (i.e. a shallow decay) and a final steeper decay. It has been found that this last part has a common behavior among BdHN events [6]. This peculiar feature may be used as a distance indicator. **Episode 4** simply consists in the SN peak optical emission, which occurs about 10 – 15 rest-frame days following the GRB itself. Optical detection may be successfully carried out as far as $z \sim 1$, with spectroscopic identification reasonably probable up to $z \sim 0.5$.

2.2 Classical hypernovae

In contrast to a BdHN event, a classical (in the sense not *binary driven*) hypernova lacks an episode 2 (see Fig. 1, left panel). This is understood as follows: if the distance between the stellar core and the companion NS is too large (and/or the companion NS is not massive enough), the latter may not accrete enough matter to undergo a gravitational collapse - which is the physical event at the origin of an episode 2. Episodes 1, 3, and 4 are still expected. Note that due to the lack of an episode 2, which is energetically the most prominent part of a BdHN, the total isotropic energy of a classical hypernova is not expected to exceed at most a few 10^{52} erg.

3. Binary compact object mergers

As pointed out in the literature (e.g. [13]), compact object mergers are prime candidates to explain short GRB events. There is indeed convincing circumstancial evidence pointing to this class of progenitors: the host galaxies of short GRBs (which are both early type and late type with old stellar populations), the absence to deep limits of associated SNe, and the offset from the associated host are important arguments. But just as BdHNe differ from classical hypernovae, we expect the merger of two compact objects to have markedly different energetics depending on whether a black hole is formed or not [12].

3.1 NS-NS or NS-WD merger leading to a NS remnant

Both NS – WD mergers and double NS mergers are likely candidates for the less energetic ($E_{iso} \lesssim 10^{52}$ erg) short GRBs (see Fig. 2, left panel). A detailed simulation of NS - WD mergers is

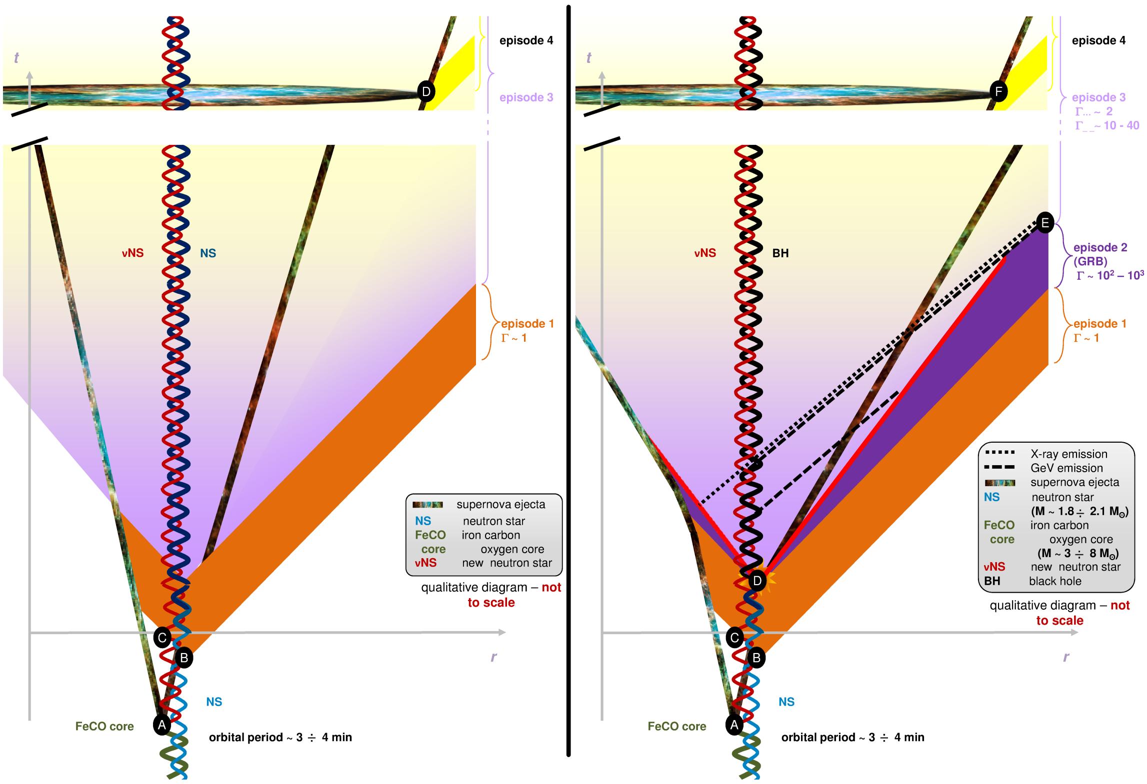

Figure 1: *Left panel*: Space-time diagram of an hypernova event. The initial configuration consists of an evolved (likely iron-carbon-oxygen) stellar core and its companion neutron star. At point A, the core undergoes a supernova and leaves a new neutron star (νNS) remnant. At point B, the companion neutron star starts to accrete matter from the supernova ejecta: this marks the beginning of Episode 1. Point C shows the beginning of the interaction of the νNS with Episode 1. The companion NS does not accrete enough matter to exceed its critical mass: no Episode 2 is emitted, on the contrary to a BdHN event (right panel). Finally, after $t \sim 10(1+z)$ days in observer frame, the supernova peaks in the optical due to ^{56}Ni decay (point D). *Right panel*: Space-time diagram of a binary driven hypernova event. The initial configuration is similar to the hypernova case - an evolved stellar core and a companion neutron star. At point A, the core undergoes a supernova and leaves a new neutron star (νNS) remnant. At point B, the companion neutron star starts to accrete matter from the supernova ejecta: this marks the beginning of Episode 1. Point C shows the beginning of the interaction of the νNS with Episode 1. When the companion NS has accreted enough matter to exceed its critical mass, it collapses to a black hole and emits a fireshell (point D). This is the start of Episode 2. Point E shows the transition between the ultra-relativistic Episode 2 and the mildly relativistic Episode 3. Finally, after $t \sim 10(1+z)$ days in observer frame, the supernova peaks in the optical due to ^{56}Ni decay (point F). Details in [12].

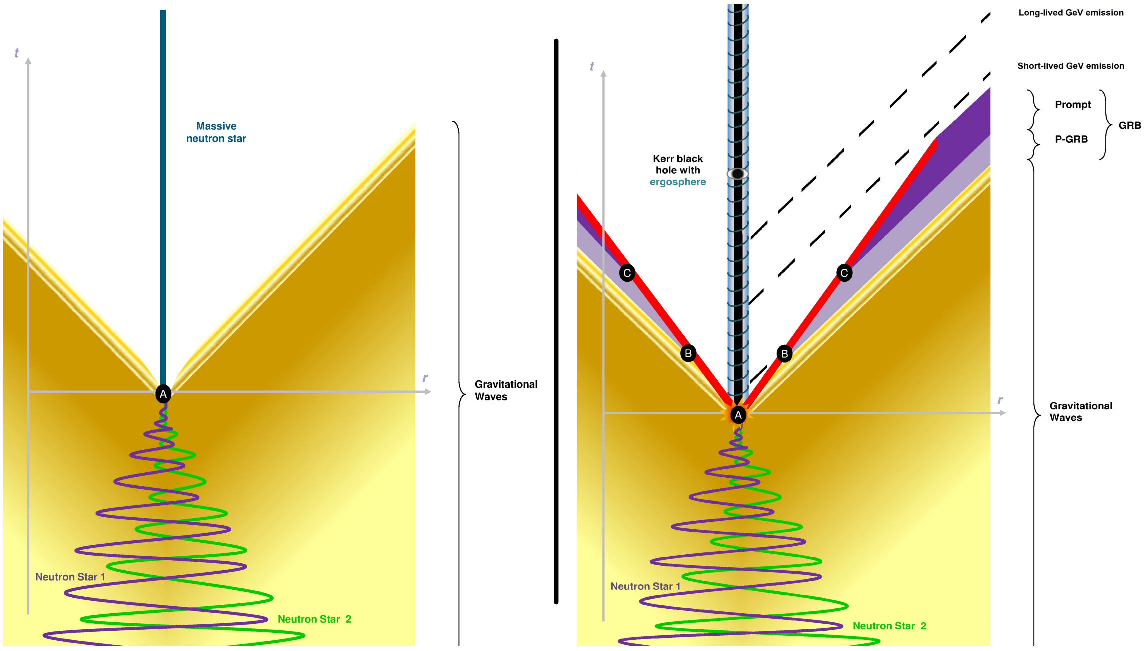

Figure 2: *Left panel*: Space-time diagram of an NS - NS merger leading to a NS remnant. The initial configuration consists of two neutron stars whose combined mass does *not* exceed the critical mass. The binary orbit shrinks due to gradually more intense gravitational wave emission, until merger finally occurs (point A). *Right panel*: Space-time diagram of an NS - NS merger leading to a BH remnant. The initial configuration consists of two neutron stars whose combined mass *exceeds* the critical mass.The binary orbit gradually until merger finally occurs (point A). The formation of a black hole implies the emission of a fireshell: a GRB event is observed (points B and C).

currently in preparation. NS – NS mergers have been explored more extensively in the literature. In particular, a set of papers ([14] and references therein) relevant to the present case develops the idea of the formation of an e^+/e^- self-accelerating plasma via neutrino - antineutrino annihilation during the merger. In this framework, the maximum energy budget is $< 10^{52}$ erg, in line with our expectations.

3.2 NS – NS merger leading to a BH remnant

If the combined mass of the two merging neutron stars exceeds the critical mass, a black hole is likely to form. As a result, following the predictions of the fireshell model, an energetic GRB should be emitted and would appear as a genuine short GRB (see Fig. 2, right panel). In particular, the genuine short GRB 090227B has been addressed in detail within the fireshell model, and has been found to be a likely outcome of an NS – NS merger [7]. Under overall charge neutrality condition, the NL3 nuclear model for a non-rotating NS critical mass gives a critical mass $M_{crit} = 2.67 M_\odot$ [15].

4. Conclusion

We presented recent developments in the classification of GRBs within the fireshell model. Binarity is a key element, since it is expected that all GRBs originate in composite events - either through compact object mergers or hypernovae. An important point lies in the fact that the energetics of a GRB are largely determined by the formation, or lack thereof, of a black hole. Ongoing work focuses on better characterization of the different progenitor families, and on reaching a more detailed understanding of the prominent observational features - among which the scaled X-ray afterglow and the GeV component.

References

[1] C. Kouveliotou, C. A. Meegan, G. J. Fishman, N. P. Bhat, M. S. Briggs, et al., *Identification of two classes of gamma-ray bursts*, *ApJ*, **413** (1993) 101

[2] M. Tavani, *Euclidean vs. non-Euclidean Gamma-Ray Bursts*, *ApJ*, **497** (1998) L21

[3] Ruffini, R., *Proceedings of the Twelfth Marcel Grossmann Meeting on General Relativity*, World Scientific, Singapore (2011)

[4] L. Izzo, R. Ruffini, A. V. Penacchioni, et al., *A double component in GRB 090618: a proto-black hole and a genuinely long gamma-ray burst*, *A&A*, **543** (2012) A10 [arXiv:1206.2887]

[5] T. Damour, R. Ruffini, *Quantum Electrodynamical Effects in Kerr-Newmann Geometries*, *Physical Review Letters*, **35** (1975) 463.

[6] G. B. Pisani, L. Izzo, R. Ruffini, C. L. Bianco, M. Muccino, A. V. Penacchioni, J. A. Rueda, Y. Wang, *Novel distance indicator for gamma-ray bursts associated with supernovae*, *A&A*, **552** (2103) L5 [arXiv:1304.1764]

[7] M. Muccino, R. Ruffini, C. L. Bianco, L. Izzo, A. V. Penacchioni, *GRB 090227B: The Missing Link between the Genuine Short and Long Gamma-Ray Bursts*, *ApJ*, **763** (2013) 125 [arXiv:1205.6600]

[8] M. Kovacevic, L. Izzo, Y. Wang, M. Muccino, M. Della Valle, L. Amati, C. Barbarino, M. Enderli, G. B. Pisani, L. Li, *A search for* Fermi *bursts associated to supernovae and their frequency of occurrence*, *A&A*, **569** (2014) A108 [arXiv:1408.6227]

[9] R. Ruffini, C. L. Bianco, F. Fraschetti, S.-S. Xue, P. Chardonnet, *On a Possible Gamma-Ray Burst-Supernova Time Sequence*, *ApJ*, **555** (2001) L117 [arXiv:astro-ph/0106534]

[10] R. Ruffini, M. G. Bernardini, C. L. Bianco, L. Caito, P. Chardonnet, M. G. Dainotti, R. Fraschetti, R.Guida, G. Vereshchagin, S.-S. Xue, *The Role of GRB 031203 in Clarifying the Astrophysical GRB Scenario*, *ESA-SP* 622 (2007) 561 [arXiv:0705.2456]

[11] R. Ruffini, M. G. Bernardini, C. L. Bianco, et al. *11th Proc. Marcel Grossmann Meeting*, World Scientific Publishing, Singapore (2008) 368

[12] R. Ruffini, Y. Wang, M. Enderli, M. Muccino, M. Kovacevic, C.L. Bianco, A.V. Penacchioni, G.B. Pisani, J.A. Rueda, *GRB 130427A and SN 2013cq: a multi-wavelength analysis of an induced gravitational collapse event*, *ApJ*, **798** (2015) 10 [arXiv:1405.5723]

[13] E. Berger, *Short-Duration Gamma-Ray Bursts*, *Annual Review of Astronomy and Astrophysics*, **52** (2014) 43 [arXiv:1311.2603]

[14] J. D. Salmonson & J. R. Wilson, *A Model of Short Gamma-Ray Bursts: Heated Neutron Stars in Close Binary Systems*, *ApJ*, **578** (2002) 310

[15] R. Belvedere, D. Pugliese, J. A. Rueda, R. Ruffini, & S.-S. Xue, *Neutron star equilibrium configurations within a fully relativistic theory with strong, weak, electromagnetic, and gravitational interactions*, *Nuclear Physics A*, **883** (2012) 1