論文の内容の要旨

Numerical simulations of the collapsar jets of Gamma-Ray Bursts (ガンマ線バーストのコラプサーモデルにおけるジェットの数値シミュレーション)

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The model of Long GRBs: The collapsar model

The collapsar model refers to a known stellar object (WR stars) and a common scheme in astronomy (BH-accretion disc system) to explain the launch of a highly relativistic jet, through which the prompt emission of GRBs can be explained (the fireball model: Piran 2000). The model is supported by the observations indicating a high SFR and a low metalicity in LGRB host galaxies (Berger et al., 2007 & Savaglio et al., 2009). Furthermore, observations of LGRB sites confirm their link to SN explosions, and thus to massive stars death (Iwamoto et al., 1998). Finally, special-relativistic numerical calculations on WR star models did confirm the collapsar scenario and its capacity to explain the general properties of GRBs (MW99 & Aloy et al., 2000). Hence, the wide popularity and acceptance of the collapsar model in GRB community.

Numerical collapsar: A framework to study GRBs

The cosmological distance makes it extremely difficult to understand GRBs through observations alone. The numerical approach, using the collapsar model is a powerful tool, and might be the sole approach to investigate some of GRB features. Thus, numerical investigations of the collapsar model using 2D codes have flourished since the collapsar establishment.

Previous numerical collapsars and the engine duration

Many of the previous numerical collapsars considered durations in the domain of ~50 – 100 seconds, and energies > 10^{52} ergs (Figure 1). This choice of long durations was considered as it favors the launch of the, traditional, energetic and highly–relativistic jets (thus explain some particularly extreme GRBs). The collapsar model focuses on the "energetic GRBs" relating them to extreme conditions, where long engines can be activated. It states that GRB engines/jets are *"an extreme case, in extreme conditions"*. However, it does not exclude short engines. Thus one would expect that these extreme engines/jets are one exceptional – rare – case, and much diverse engine durations exist in nature, and account for the diversity of the observed GRBs (Lazzati et al., 2012). Bromberg et al., (2012) argued in this sense as the distribution of engine durations seems to have a power law index < – 3, and thus a large number of short engines would be occurring.

GRBs diversity: A challenge of the collapsar scenario?

Recently, one arising issue in GRB astronomy is GRB diversity and irregularities. In pre-Swift era GRBs referred to energetic, cosmological, and highly relativistic events (Γ > 100) (Piran 2005). Nowadays, and after a decade of Swift service, the term GRB is significantly diverse, and the "extreme GRBs" are just one class among many others. For instance, in terms of the isotropic equivalent energy, GRB energies are spread over 6 orders of magnitude (Amati et al., 2010). Among the newly discovers classes, is *low luminosity* GRBs class (Soderberg et al., 2004b), with the isotropic equivalent energy $E_{iso} \leq 10^{49}$ erg (Laing et al., 2007 & Bromberg et al., 2011a).

llGRBs origin

Since its discovery, *ll*GRBs class is at the center of attention. Its study allows understanding the universal picture of GRBs phenomena in the universe, from low redshift to high redshift, and from soft to hard energy domain. *ll*GRBs present several peculiar features that make them debated. Apart from their softness, *ll*GRBs present two unusual features: High rates and strong SN connection. While the rate of the standard GRBs is ~1 Gpc^{-3} yr^{-1}, *ll*GRBs rates are much higher: Coward 2005: ~220 Gpc^{-3} yr^{-1}; Piran et al., 2006: ~110^{+180}_{-20} Gpc^{-3} yr^{-1}; Soderberg et al., 2006: ~260^{+490}_{-190} Gpc^{-3} yr^{-1}; Cobb et al., 2006: ~300 times GRBs; Liang et al., 2007: ~325^{+352}_{-177} Gpc^{-3} yr^{-1}; Guetta & Della Valle 2007: ~380^{+620}_{-225} Gpc^{-3} yr^{-1}. Such rates suggest that the standard GRBs are a minority in numbers in nature, thus the importance of the study of *ll*GRBs.

*ll*GRBs are discussed on their origin, on whether they do arise from the classical collapsars and about their link to classical GRBs (Yamazaki et al., 2004 & Bromberg et al., 2011a). There have been some attempts to use the collapsar to explain *ll*GRBs, but a classical collapsar (engine with: $T_{inj} >> T_{breakout}$) shows serious limitations (Cobb et al., 2006). A more diverse collapsar is therefore needed to explore the origin of *ll*GRBs and investigate a possible unification with the traditional GRBs. Bromberg et al., (2011a & 2012) findings suggest that *ll*GRBs are produced by different engines ($T_{inj} < T_{breakout}$), which is in conflict with the, above, unification model. Hence: *"are llGRBs from standard GRBs engines? if not what alternative model would explain them?"*

The motivation

***In general**: To explore a diverse version of the collapsar model, which would reproduce, and explain, the diverse nature of GRBs, as seemingly in the observations.*
***In particular**: To investigate the origin of llGRBs, by testing the previously suggested origins, and to which extent llGRBs peculiar features (High rate and SN connection) can be explained.*

The research plan

I consider different simulations of the collapsar model. I aim to study not just the classical event of the collapsar, but diverse events as the observations suggest. I keep all the jet properties constant except the engine duration T_{inj}. I choose the collapsar engine duration as the main parameter because the engine is poorly understood, as the BH surrounding environment is very complex. Hence this might contribute to exploring the mysterious nature of collapsars' engine. The different engine durations produce *long* and successful jets, as well as *brief* and failed jets. This enables to search for an engine specific duration domain that explains *ll*GRBs' peculiar features of: a high rate relative to standard GRBs, and a strong SN connection.

Originality

My numerical investigation is on a wide range (largest to date; Figure 1). In particular investigating short duration, not deeply investigated yet. I derive the ratio of rates *ll*GRBs/GRBs, and the SNe energies for the different models, enabling an original comparison (for the first time).

The results

The engine duration was found to dramatically affect all the jet hydrodynamic properties. In summary, the engine duration was found to influences the following:
- The breakout time: The evolution of the jets inside the progenitor was different, for the different engine durations. As a result, the breakout time was dramatically affected and varied significantly, generally decreasing, as the engine duration is set longer.
- Jet phases and light curve: The number of radiative phases was found to vary from one, for the *brief* engines, to two for *short* and *intermediate* engines, and three for *long* engines. Hence, the hydrodynamic properties and the structure of light curves differ from an engine to another.

- Collimation and Lorentz factor: *Brief* engines produce poorly collimated outflow and mildly relativistic jets. Generally, the longer the engine duration is the better collimated and the higher the Lorentz factor is. However, for *long* engines this trend is slightly inversed.
- llGRBs vs. GRBs (Figure 2): The shorter the engine duration is, the higher the probability of observing the produced jet. Thus, the collapsar event of *brief* engines possesses the higher probability of observation. I found that *brief* engines alone ($T_{inj} < T_{Breakout}$), can produce *ll*GRBs at huge rates, in the range of 100-1000 times GRBs. This is in agreement with the estimated rates of *ll*GRBs. Thus, *brief* engines are excellent candidates for *ll*GRBs, explaining *ll*GRBs properties and their high rates. By considering several engine duration distributions, I found that a power-law distribution with an index ≥ 1, would explain the rates of *ll*GRBs and GRBs in the universe.
- ***GRB vs. SN:*** By considering the assumption that non-relativistic outflow from the jet cocoon, would contribute in the SN explosion (as in Zhang et al., 2003), I showed that the SN explosion is about one order of magnitude stronger in the case of *brief* engines (linked to *ll*GRBs). Thus, I give a possible explanation of the observational trend of *ll*GRB-SN and GRB-SN connections.

Discussion and Conclusion:

Considering the scheme of the "unification model" (Yamazaki et al., 2004), *brief* ($T_{inj} < T_{Breakout}$) and *long* engines ($T_{inj} >> T_{Breakout}$) present an interesting contrast. On one hand, off-axis observations of *brief* (failed) jets, would explain *ll*GRBs with their high rates, soft properties and SN signatures. Such events would dominate at very low redshifts. On the other hand, on-axis observations of *long* engines jets, could explain GRBs' energetic properties and the weaker SN connection. Such events would dominate at high redshift.

As shown in Figure 3, by varying the engine duration time, I confirm Bromberg et al., (2011a & 2012) finding, that *ll*GRBs origin is different from the standard GRBs (successful jets); as *ll*GRBs are well explained with engine durations shorter than the breakout time (failed jets). I show that successful jets alone cannot unify *ll*GRBs with GRBs, as the rate is much lower than the observations. Also, I confirm Cobb et al., (2006) argument that *ll*GRB rates cannot be explained with a typical GRB jet alone (the ratio of rates *ll*GRBs/GRBs cannot exceed ~65; < 100). The second finding is that failed jets make powerful cocoons and thus luminous SNe, while successful jets show much weaker cocoons. As *ll*GRBs are strongly connected to SN explosions, this presents an additional argument in favor of the failed jet origin for *ll*GRBs (Figure 4).

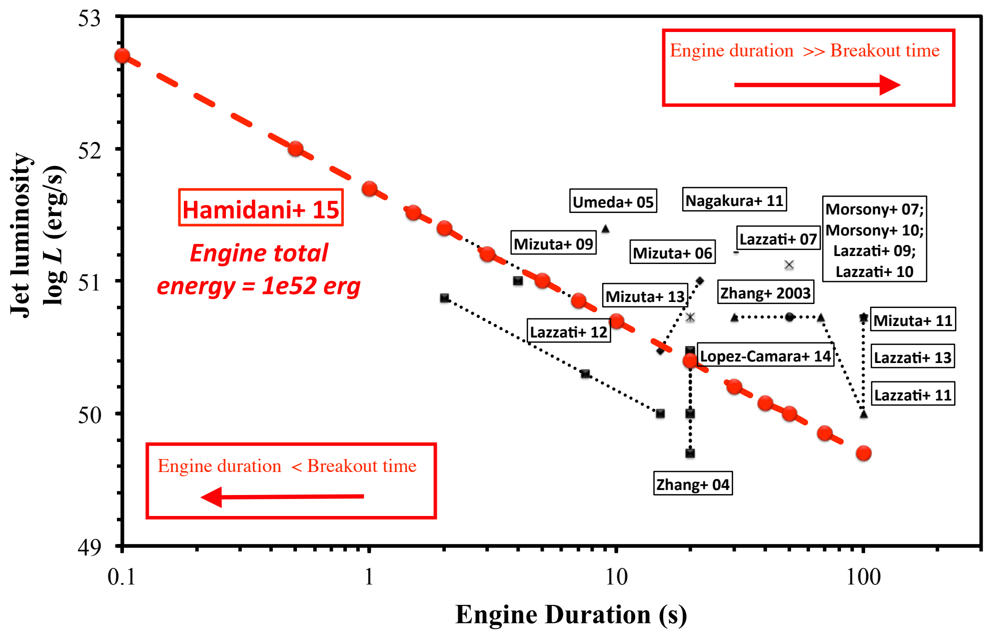

Figure 1: The wide duration domain considered in this study, in comparison with previous 2D simulations of the collapsar.

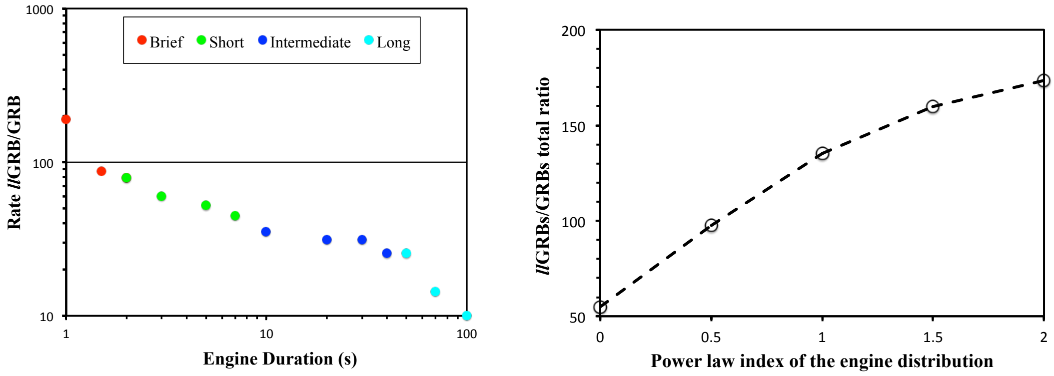

Figure 2: (Left panel) The ratio of rates *ll*GRBs/GRBs, as a function of the engine duration. (Right panel) The total rates ratio considering all the engine models, for different engine power law distributions. Only *brief* engines produce as high rates of *ll*GRBs as the observations suggest. Thus, a power law index of ≥ 1 would explain *ll*GRBs rates in the nearby universe.

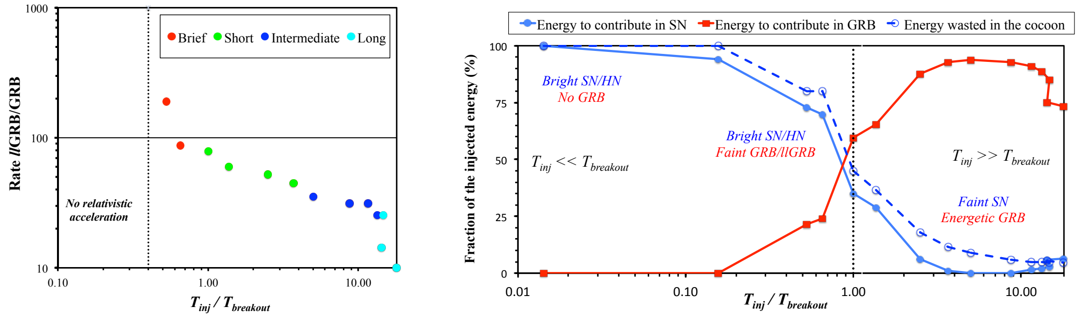

Figure 3: (Left panel) The ratio of rates *ll*GRBs/GRBs and (on the right) energy acceleration, expressed as a function of $T_{inj}/T_{breakout}$. This summarize the findings: *Brief* engines, or failed jets ($0.1 < T_{inj}/T_{breakout} < 1$) reproduce very well the features of *ll*GRBs: i) a high rate (~100 times that of GRBs) & implies a potentially strong SN, ii) longer engines (with $T_{inj}/T_{breakout} >> 1$) reproduce standard GRBs properties: A strong/relativistic jet, but does not intend a powerful/clear SN

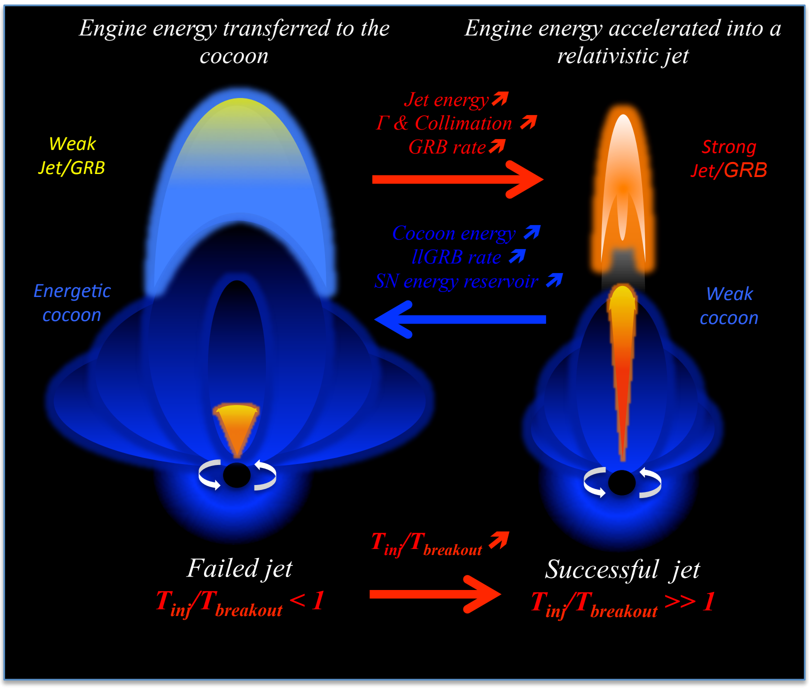

Figure 4: An illustration showing the main finding of this work.