Do Long Gamma-Ray Burst Engines Speak a Stochastic or Deterministic Language?

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1. Introduction

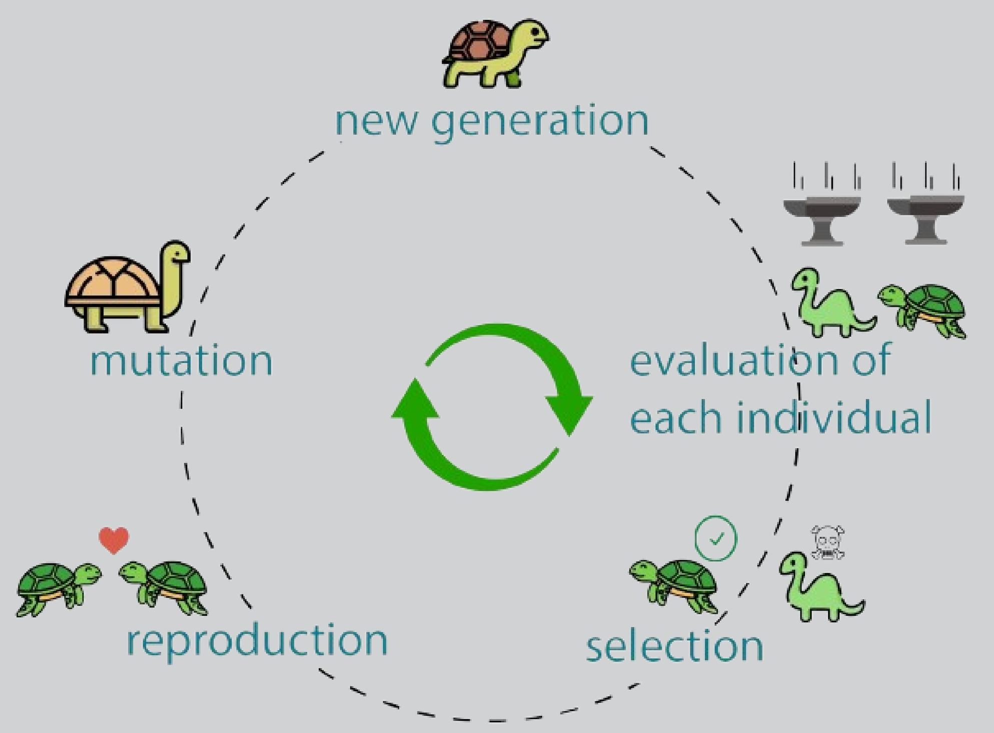
A successful description of the **inner engine activity** of long gamma-ray bursts (LGRBs) holds the key to deciphering the variety and complexity exhibited by their light curves (LCs). Although the knowledge of GRB spectral properties has made huge strides thanks to technological advancement, temporal properties remain mostly unintelligible. In particular, an open question is whether they originate from deterministic or stochastic processes. In this respect, we present a common description of LGRB LCs as the outcome of a **stochastic pulse-avalanche process**, resulting from the refinement of a previous model [1]. The model parameters were optimised with a **genetic algorithm** (GA), and tested on three independent datasets of LGRBs detected by three different experiments: **CGRO/BATSE**, ***Swift*/BAT**, and ***Fermi*/GBM**. We found that a relatively simple stochastic process operating in a nearly critical regime can successfully reproduce several average temporal properties of the population of real LCs, providing clues to the dynamical behaviour of the LGRB inner engine. In addition, this model offers a credible tool to simulate from scratch synthetic LCs for future experiments.

2. Stochastic Pulse-Avalanche Model

The model assumes that each GRB LC is a unique **random realisation** of a common stochastic process that works close to a critical regime, with parameters confined to narrow ranges [2]. In this framework, spontaneous primary (*parent*) pulses trigger secondary (*child*) pulses in a **recursive manner** until the system transitions to a subcritical regime. The **superposition** of parent and child pulses makes up the GRB LC. Each pulse follows a Gaussian rise and exponential decay, with the amplitude (in erg cm^{-2} s^{-1}) sampled from a broken power-law probability density function. Overall, the model totals eleven parameters to be optimised by the GA.

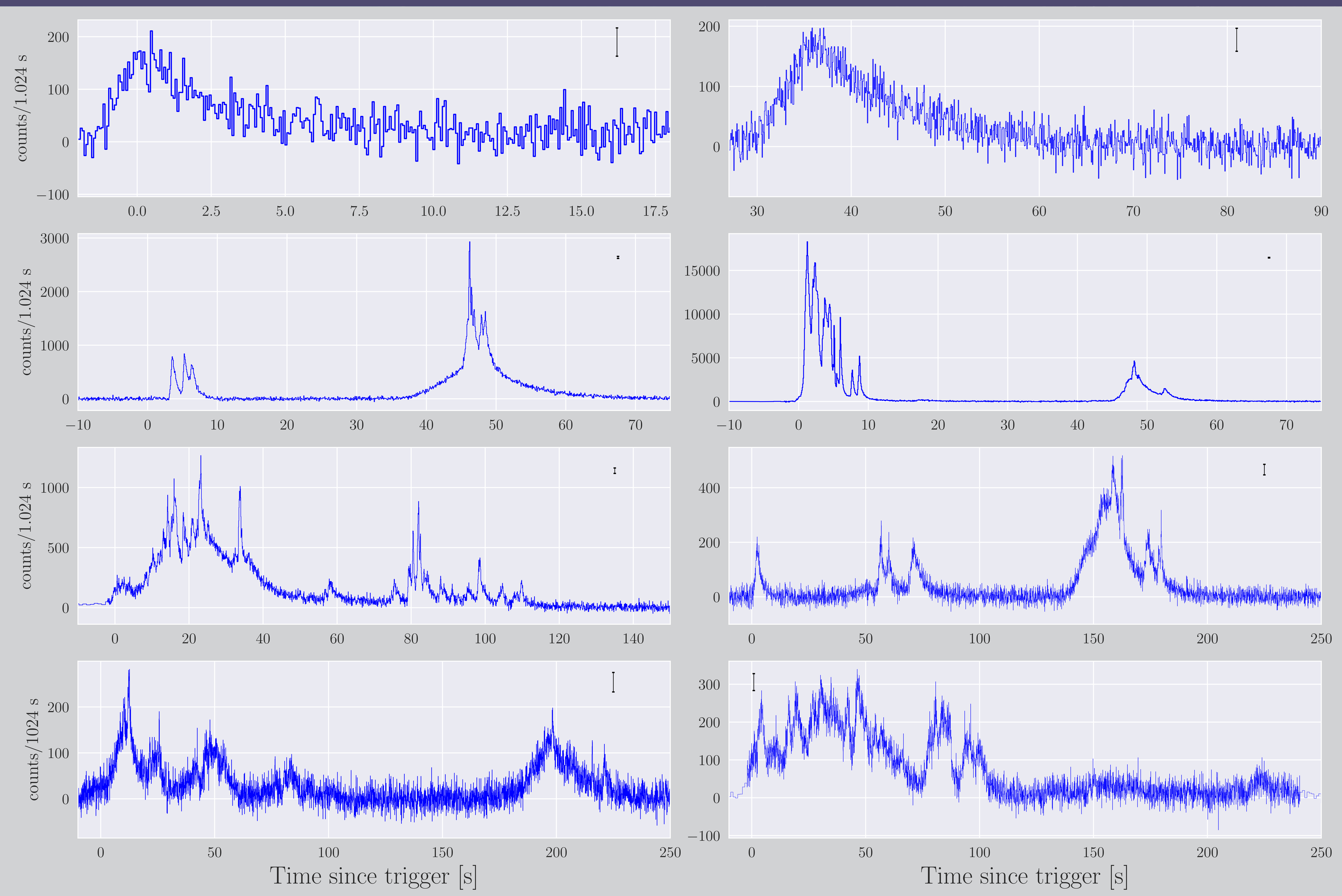
3. Genetic Algorithm

A genetic algorithm (GA) improves the **average fitness** of a population of solutions to an optimisation problem based on specific **metrics**. Over successive generations, the population evolves, eventually converging towards the optimal solution. Each solution (***individual***) is encoded as a string of parameters analogous to chromosomes in biology. The fitness of these individuals determines which ones will **mate**, combining their genetic information to produce the offspring.



Each individual represents a sequence of possible values for the eleven model parameters.

4. Play time! Guess real vs. fake BATSE LCs



[**Solutions**: Row 1: Left, Row 2: Right, Row 3: Left, Row 4: Right.]

5. Conclusions

We simulated LCs that reproduce several of the **average temporal properties** of real LCs of LGRBs belonging to CGRO/BATSE, *Swift*/BAT, and *Fermi*/GBM catalogues. For the first time, we proved that the **peak flux distribution** of individual pulses can be successfully modelled as a **broken power-law** and constrained under the assumption of a stochastic model. Our results further support the hypothesis that central engines of LGRBs, or, more generally, the source of variability driving the dissipation mechanism, operates close to a **critical regime**. Within the internal shock model, the avalanche process could stem from fragmentation driven by magneto-rotational, gravitational, and/or viscous instabilities in the accretion disc of a hyper-accreting BH. Alternatively, the avalanche mechanism could result from magnetic energy dissipation through runaway sequences of reconnection events, as predicted in the ICMART model [3].
The source code for our algorithm, along with all scripts used for data analysis and visualisation, is publicly available on GitHub.

6. References

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6. Scan me: GitHub