High-mass X-ray Binaries: Illuminating the Passage
from Massive Binaries to Merging Compact Objects
Proceedings IAU Symposium No. 346, 2019
L. M. Oskinova, E. Bozzo, T. Bulik & D. Gies, eds.

doi:10.1017/S1743921318007603

How pulses in short gamma-ray bursts constrain HMXRB evolution

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Abstract. We demonstrate how pulse structures in Short gamma-ray bursts (SGRBs), coupled with observations of GRB/GW 170817A, constrain the geometries of dying HMXRB systems composed of merging neutron stars.

Keywords. X-rays: binaries, gamma rays: bursts, methods: data analysis, methods: statistical

1. Introduction

Binary neutron stars represent an HMXRB evolutionary end resulting in the creation of short gamma-ray bursts (SGRBs). These luminous flashes of $\gamma-$radiation occur after neutron stars merge following the decay of their orbits. The most powerful evidence linking neutron star mergers to SGRBs has been the LIGO gravitational wave 'chirp' of GW 170817 (Abbott *et al.* 2017) in which two compact objects having masses between $1.17 M_\odot$ and $1.60 M_\odot$ and a combined mass of $2.74 M_\odot$ merged. SGRB 170817A was observed 1.7 seconds later by the GBM experiment on Fermi. This SGRB had a duration of roughly 2 seconds (Goldstein *et al.* 2017) and a Lorentz factor of $\Gamma > 10$ (e.g., Zou *et al.* 1995).

The dominant method of emission in GRBs is via $\gamma-$ray pulses. GRB pulse light curves are not simple smoothly-varying 'bumps.' Instead they generally exhibit structure that cannot be explained by stochastic background variations. Furthermore, this structure often has a wavelike shape that gives a GRB pulse a triple-peaked rather than a single-peaked appearance. Typical GRB pulses evolve from hard to soft but re-harden as the intensity re-brightens; this behavior is true for both SGRBs and LGRBs (long GRBs).

2. GRB Pulse Structure

In order to characterize GRB pulse structure, Hakkila *et al.* (2018a) classified GRB pulses based on their complexity as determined by a simple monotonic 'bump' overlaid by an identifiable 'wavy' structure; this simple approach is often effective. Pulses were classified as *simple* when they could be fitted by a monotonic pulse alone (using the Norris *et al.* 2005 pulse shape), *blended* when they could be fitted by a monotonic pulse with significant wavy residual structure (characterized by the Hakkila & Preece 2014 residual function), *structured* when fits were improved but not completely adequate, and *complex* when pulse light curves were too structured for a good combined fit.

Examples of SGRB pulses containing different amounts of structure are shown for BATSE SGRBs 0373 (simple), 2896 (blended), 5564 (structured), and 4955 (complex)

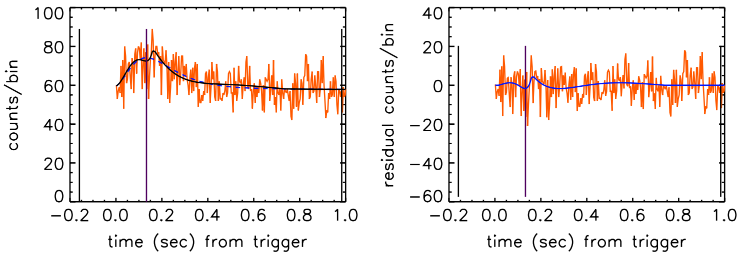

Figure 1. Simple SGRB pulse BATSE 0373. Pulse fit (left) and residual fit (right).

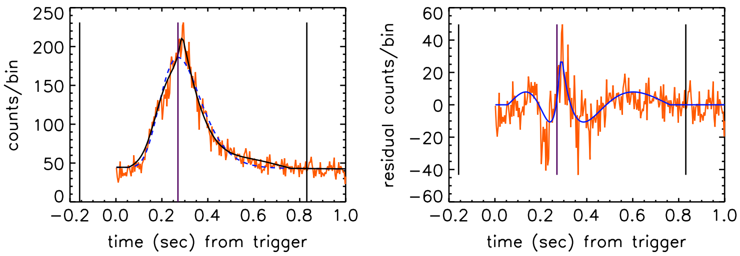

Figure 2. Blended SGRB pulse BATSE 2896. Pulse fit (left) and residual fit (right).

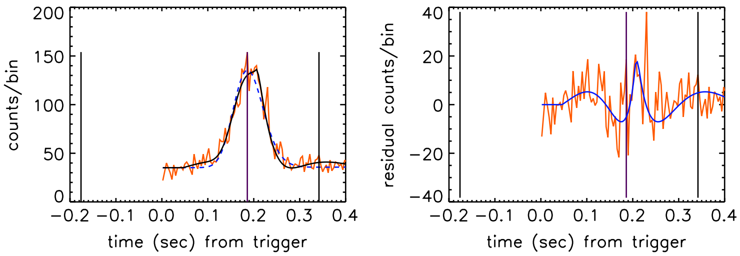

Figure 3. Structured SGRB pulse BATSE 5564. Pulse fit (left) and residual fit (right).

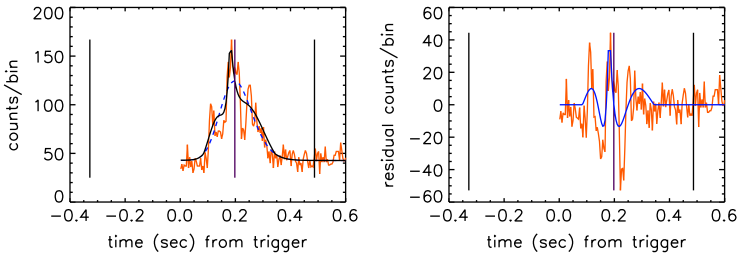

Figure 4. Complex SGRB pulse BATSE 4955. Pulse fit (left) and residual fit (right).

in Figs. 1 through 4. In each figure, the left panel demonstrates the fit obtained with the Norris *et al.* (2005) pulse shape (dashed blue line) and the Norris *et al.* (2005) pulse shape combined with the Hakkila & Preece (2014) residual structure (solid black line). The right panel indicates the residuals once the Norris *et al.* (2005) fit has been removed, overlaid by the Hakkila & Preece (2014) residual fit (solid blue line).

Detector signal-to-noise ratio (S/N) and temporal resolution are capable of smearing out intrinsically complex GRB structures and of causing GRB pulses to appear as

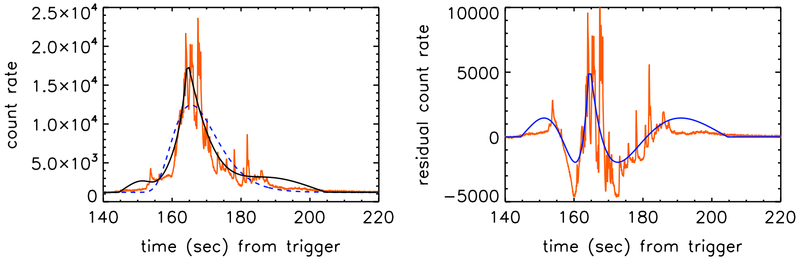

Figure 5. LGRB BATSE 7301p2, a complex, extremely bright pulse. Pulse fit (left) and residual fit (right).

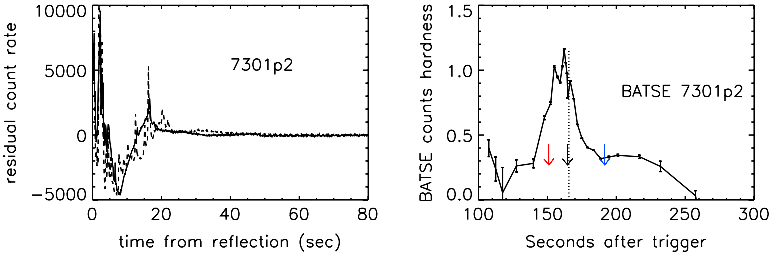

Figure 6. LGRB BATSE 7301p2. Time-reversed and stretched residuals (left) and spectral hardness evolution (right).

either monotonic shapes augmented by the triple-peaked structure or as simple monotonic shapes. Thus a GRB pulse's appearance is a combination of intrinsic structures and instrumental smearing effects. The effects of S/N on both SGRB and LGRB pulse classification have been demonstrated by Hakkila *et al.* (2018b) and Hakkila *et al.* (2018b).

3. Constraints Imposed by Time-Reversed and Stretched Residuals

Since instrumental effects can make it hard to delineate GRB pulse structure from noise, interpretation of GRB pulse physics is best understood through the study of bright GRB pulses. Hakkila *et al.* (2018b) studied six of the brightest BATSE LGRB pulses and demonstrated that the residual structure model employed previously was too simple and incomplete for describing the residuals of these pulses because the residual structure extends far beyond the temporal boundaries containing the three peaks. Furthermore, the extended wavelike structure is shown to have strange characteristics: it is both *time-reversible* and *stretched* around a *time of reflection*. In other words, the pulse residuals following the time of reflection have a memory of the residuals preceding it, but these events are repeated in reverse order after undergoing a dilation at the time of reflection.

An example of this is shown for LGRB BATSE pulse 7301 p2 in Fig. 5 and Fig. 6. The left panel of this figure shows the model fits for the pulse, both including (solid black line) and excluding (dashed blue line). The residual model is able to fit part of the residual light curve, but is inadequate in identifying and fitting all of the structure (right panel of Fig. 5). The left panel of Fig. 6 uses a new approach that recognizes the time-reversed and stretched structure of the residual model without being dependent on that model's functional form. The residuals are folded over in time and stretched until they line up with one another, so the residuals prior to the time of reflection (solid line) are shown overlaid by the time-reversed and stretched residuals preceding the time of reflection (dashed line). Further evidence that these residuals are linked together in a chain, rather than distributed randomly, is shown in the hardness evolution plot of the pulse (Fig. 6).

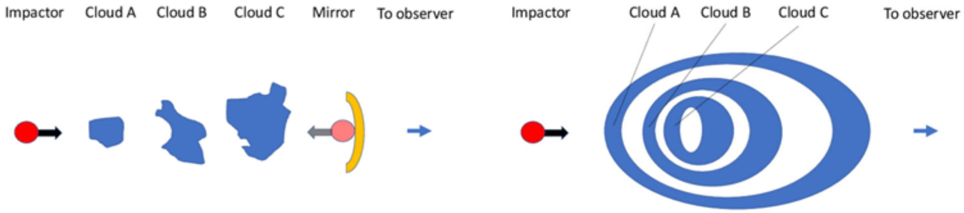

Figure 7. Two possible kinematic models for explaining the time-reversed and stretched residuals found in GRB pulse light curves: the mirror model (left panel) and bilaterally-symmetric model (right panel).

Here the pulse hardness generally evolves from hard-to-soft, with a re-hardening at each residual peak.

Time-reversed and stretched pulse residuals place remarkably strict constraints on GRB models. They couple events that happen at the beginning of a pulse with those that happen towards the end, but they further indicate that the conditions responsible for creating the pulse structure must repeat in reverse order and be time-dilated. We demonstrate two simple models in which pulse light curves with the observed characteristics might be created by jetted GRB material. We note that these models are driven solely by kinematics and geometry rather than by a specific radiation mechanism.

The first *mirror model*, shown in the left panel of Fig. 7 consists of a relativistically-moving *impactor* (shown as a red circle) ejected from the central engine. This impactor might be a soliton (shock wave) or a plasma blob that interacts with other plasma clouds in the jet (in blue) to produce radiation. The impactor slows upon striking a mirror (in yellow; presumably the jet head), which allows the clouds to catch up with it in the opposite order. The blueshifted initial motion of the impactor through the clouds produces beamed emission (A.B.C) followed by emission that is less-strongly blueshifted (C...B...A).

The second *bilaterally-symmetric model*, shown in the right panel of Fig. 7, is composed of clouds distributed in a bilaterally-symmetric fashion along the impactor's path, producing the beamed (A.B.C.C...B...A) emission pattern.

4. Constraints Imposed by the Rarity of Pulses

The standard definition of a pulse refers to a single-peaked monotonic bump. Using this definition, observers are misled into thinking that a typical GRB generally contains many pulses. The recognition that peaks are linked temporally (such that the time-reversed and stretched residuals can be used to identify all the peaks associated with a single pulse), allows the number of pulses in a GRB to be reduced dramatically.

The recent study of Hakkila *et al.* (2018b) finds that 90% of SGRBs are single-pulsed, and most of the remaining 10% are double-pulsed. Thus the mechanism producing SGRBs generally does so in the form of a single structured pulse, but this can also occur less frequently as two or maybe three pulses. Since SGRBs are produced by colliding neutron stars, it seems unlikely that each interaction is capable of producing more than a single blast wave. We thus turn to GRB geometry to explain multi-pulsed bursts.

5. An SGRB Model that Accounts for Pulse Structure and Rarity

We can use the constraints imposed by GRB pulse structure and by the rarity of multi-pulsed SGRBs, in conjunction with theoretical models of merging neutron stars, to improve physical models. Standard models of merging neutron stars suggest that they produce a thick accretion disk with a tail extending behind it as it rotates (*e.g.* Rosswog

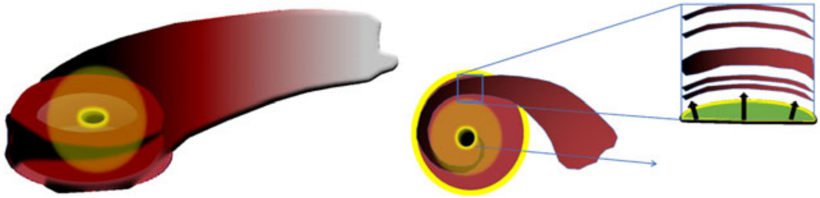

Figure 8. 3D model of ns-ns merger as seen from the side (left) and top (right) views. Most lines-of-sight produce single-pulsed SGRBs, but a line-of-sight through the accretion tail will produce two pulses. The accretion disk structure is similar to that found in the axially-symmetric model shown in Figure 7.

et al. 2014). The timescale for the existence of this disk is very short (< 20 ms). From the perspective of our model, we can consider the radial distribution of the disk to be the 'jet' and density variations in the disk itself to comprise the distribution of clouds within the jet.

In order to match our observations, the merging neutron stars likely produces a soliton at the moment of black hole formation, and this impactor expands spherically outward (denoted by the yellow sphere in Fig. 8). This model can reproduce the time-reversed and stretched residuals found in SGRB pulse light curves if the radial distribution of material is bilaterally-symmetric (seen in the enlargement of the accretion disk radial structure found on the far right side of Fig. 8). We note that double-pulsed bursts can occur if the accretion tail is pointed along the observer's line-of-sight, so that the observer sees two emitted pulses each with similar time-reversed and stretched structures. The timescale of each pulse is essentially the light travel time of the disk and of the tail, and the interpulse separation is essentially the light travel time of the gap between the disk and the tail.

This attempt to model SGRBs is among the first to incorporate constraints imposed by observations of GRB pulses. Other models are also possible, but each must be consistent with the pulse observations. We continue to study and explore these models for both SGRBs and LGRBs.

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