CORRELATIONS BETWEEN LAG, LUMINOSITY, AND DURATION IN GAMMA-RAY BURST PULSES

JON HAKKILA,1 TIMOTHY W. GIBLIN,2 JAY P. NORRIS,3 P. CHRIS FRAGILE,1 and JERRY T. BONNELL4

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ABSTRACT

We derive a new peak lag versus peak luminosity relation in gamma-ray burst (GRB) pulses. We demonstrate conclusively that GRB spectral lags are pulse rather than burst properties and show how the lag versus luminosity relation determined from CCF measurements of burst properties is essentially just a rough measure of this newly derived relation for individual pulses. We further show that most GRB pulses have correlated properties: short-lag pulses have shorter durations, are more luminous, and are harder within a burst than long-lag pulses. We also uncover a new pulse duration versus pulse peak luminosity relation, and indicate that long-lag pulses often precede short-lag pulses. Although most pulse behaviors are supportive of internal shocks (including long-lag pulses), we identify some pulse shapes that could result from external shocks.

Subject heading: gamma rays: bursts

1. INTRODUCTION

Gamma-ray burst (GRB) prompt emission has remained enigmatic over the years, even as our understanding of afterglow physics has evolved. Time intervals containing flux increases (pulses) exhibit some general behaviors, including (1) longer decay than rise rates, (2) hard-to-soft spectral evolution, and (3) broadening at lower energies (e.g., Norris et al. 1996; Ryde 2005).

The spectral lag is the delay between photons observed in a high-energy bandpass relative to a lower energy one; it is primarily obtained through application of the cross-correlation function (CCF; Band 1997). In general, lag is an indicator of both GRB peak luminosity (e.g., Norris et al. 2000; Norris 2002) and time history morphology (Hakkila et al. 2007), with short-lag, variable bursts having greater luminosities than long-lag, smooth bursts.

The short durations, spectral evolution, and short interpulse durations of most GRB pulses suggest that they originate from internal shocks in relativistic winds (e.g., Daigne & Mochkovitch 1998; Ramirez-Ruiz & Fenimore 2000; Nakar & Piran 2002). However, some bursts exhibit a soft component indicative of afterglow onset (e.g., Giblin et al. 2002) which could be interpreted as the initial external shock. Prompt afterglow emission begins preferentially toward the end of the burst or even after the GRB ends, as suggested by several X-ray afterglows observed by BeppoSAX (Costa 2000) and Swift (Panaitescu 2007), but it can also appear at a time early enough to overlap the short-timescale emission (as observed in GRB 980923 [Giblin et al. 1999]). In addition, co-adding fluxes of many BATSE GRBs has led to observation of extended soft gamma-ray emission possibly indicating the same phenomenon (Connaughton 2002).

Internal and external shocks have both been predicted theoretically (e.g., Sari & Piran 1999), and it has been suggested that both shock types are observed within quiescent BATSE GRBs 960530 and 980125 (Hakkila & Giblin 2004). Quiescent GRBs (Ramirez-Ruiz & Merloni 2001; Ramirez-Ruiz et al. 2001) release their prompt emission in one or more distinct

1 Department of Physics and Astronomy, College of Charleston, Charleston, SC 29424-0001; hakkilaj@cofc.edu.
2 Department of Physics and Astronomy, University of North Carolina, Asheville, NC.
3 Space Science Division, NASA Ames Research Center, Moffett Field, CA.
4 UMCP/CRESST, NASA Goddard Space Flight Center, Greenbelt, MD.

emission episode (each episode contains one to many overlapping pulses). Although the prequiescent emission episodes of these two GRBs satisfy the standard internal shock paradigm, the long episodic lags, smooth morphologies, and soft spectral evolution of the later episodes are more consistent with external shocks, indirectly implying that the pulses comprising these episodes might also relate to specific types of shocks (however, see Chincarini et al. 2007). Other observations support the idea that lag can vary within GRBs, and indirectly suggest that these variations are associated with pulses (e.g., Norris 2002; Ryde et al. 2005; Chen et al. 2005). However, no study has yet isolated and delineated pulse spectral properties; to this end and to test the hypothesis that short- and long-lag pulses have different origins, we have set out to model pulses and study their spectral dependences.

2. PULSE IDENTIFICATION AND FITTING TECHNIQUE

We have developed a semiautomated pulse-identification and fitting routine using BATSE 64 ms data. The Bayesian Blocks (BB) routine (Scargle 1998) is applied to summed four-channel data and identifies regions over which counts change significantly. Each BB potentially contains a pulse, and is fit using the pulse model of Norris et al. (2005):

\[ I(t) = A \lambda \exp \left[ -\tau_b (t - t_s) - (t - t_s)/\tau_a \right], \]

where \( t \) is time since trigger, \( A \) is the pulse amplitude, \( t_s \) is the pulse start time, \( \tau_b \) and \( \tau_a \) are characteristics of the pulse rise and pulse decay, and \( \lambda = \exp \left[ 2(\tau_b/\tau_a)^{\alpha} \right] \). In addition, a two-parameter linear background model is assumed. Reasonable initial guesses are made using the starting and ending BB boundaries and the highest flux found in this BB. The nonlinear least squares routine MPFIT5 simultaneously fits all of the pulses and the background, iterating initial guesses to a convergent solution as characterized by \( \chi^2 \) per degree of freedom. Statistically insignificant pulses are deselected from the initial pulse fit using a dual-timescale threshold (Hakkila et al. 2003) and Occam’s razor. The dual-timescale threshold is chosen over a peak flux (favoring short, intense pulses) or fluence threshold (favoring long, low-intensity pulses) because it treats equally pulses peaking on short and long timescales. The reduced model is run again with fewer pulses until it converges and

5 See http://idlastro.gsfc.nasa.gov/contents.html.
only pulses brighter than the dual-timescale threshold remain. The four-channel pulse characteristics are used as starting points from which individual energy channel pulse characteristics are obtained. The process described above is repeated until convergent solutions are obtained for pulses in each energy channel.

Pulse peak lags are defined as the differences between the pulse peak times in different energy channels (pulse peak times are given by \( t_{\text{peak}} = t_p + \sqrt{\tau_1 \tau_2} \)). Pulse peak lags can be obtained for any pulse between two energy channels, although we define the standard \( l_{pp} \) as that measured between energies of 100–300 keV (BATSE channel 3) and 25–50 keV (BATSE channel 1).

Other measurable pulse properties include the pulse width \( w = (9 + 12 \sqrt{\tau_1 / \tau_2})^{1/2} \) and the pulse asymmetry \( \kappa = w / \left(3 + 2 \sqrt{\tau_1 / \tau_2}\right) \). These definitions are based on time intervals between intensities of \( A e^{-t^2} \), rather than of \( A e^{-t} \) (Norris et al. 2005). We note that the modeled pulse duration definition of \( w \) is less susceptible to statistical variations near the beginning and end of the pulse than observationally defined durations such as \( T_{90} \).

Pulse parameter uncertainties are obtained using Monte Carlo analysis because Gaussian error assumptions (Norris et al. 2005) is not always valid for \( t_p \), \( \tau_1 \), and \( \tau_2 \). These distributions often resemble lognormal or multimodal distributions, and improperly quoted uncertainties in these parameters often lead to overestimated uncertainties for pulse peak time amplitudes, durations, and asymmetries.

3. ANALYSIS

Energy-dependent pulse properties are regularly identified and extracted using this technique, even though the pulse-finding technique is energy-independent. Multilag GRBs are apparently the norm for most Long GRBs. When the signal is strong enough that pulses can be cleanly and unambiguously extracted, their characteristics are generally consistent across all energy channels (e.g., lags are observed across all energy channels in proportion to the energy channel separation). Within the limit of uncertainty, it appears that every pulse is characterized by its own lag. This is not to say that all pulses are clearly identified from one energy channel to another; there are fitting ambiguities caused by pulse overlap, and low signal-to-noise ratio (such as is found in BATSE channel 4). In addition, it is difficult to uniquely fit many overlapping pulses because a pulse’s fitted signal-to-noise ratio is not solely dependent on background; the flux of other pulses is “noise” to this fit.

We demonstrate results with the fit to GRB 950325a (BATSE trigger 3480), in which three overlapping pulses are observed with fairly high signal-to-noise ratio in all four BATSE energy channels. Fitted channel 1 and channel 3 time histories are shown in Figure 1. The CCF burst lag \( l_{\text{CCF}} = 0.014 \pm 0.009 \) s (Hakkila et al. 2007). Some properties of the extracted pulses are listed in Table 1; these include the pulse fit parameters \( l_{pp}, w, \) and \( \kappa \) as well as CCF pulse lags. Pulse CCFs have been reconstructed from multichannel pulse parameters and the burst’s Poisson background. The greatest contribution to the CCF lag is found to come from the shortest-lag, highest-intensity pulses. In fact, the CCF lag appears to be insensitive to the presence of longer lag pulses, which can appear at any time during a burst. The CCF and pulse peak lags occasionally disagree: the CCF lag of pulse 2 is demonstrably negative, even though the pulse has a moderately long pulse lag that is measured consistently across all four energy channels. We are currently exploring the effects of pulse shape on the CCF. The CCF of the original burst is essentially identical to that of the reconstructed burst, indicating that the long- and short-lag pulses have been combined to reproduce a good facsimile of the original short-lag GRB.

The sensitivity of the CCF to the shortest, brightest pulses provides an explanation for why Norris et al. (2000) find different CCF lags when their burst data are confined to different intensity regimes via an apodization technique. Their removal of the low-intensity flux predominantly removes CCF contributions from the longest duration, longest lag pulses, and improves the ability to measure the signal from the short-lag pulses.

3.1. Spectral-dependent Pulse Properties

Although we are in the early stages of analyzing GRB pulse data, it is already apparent that the vast majority of GRB pulses

| Pulse | \( l_{\text{CCF}} \) (s) |
|-------|-----------------|
| 1     | 0.006 ± 0.003   |
| 2     | -0.064 ± 0.020  |
| 3     | 0.414 ± 0.062   |

Table 1: Pulse Properties of GRB 950325a
have correlated spectral and temporal properties. Pulse lag, amplitude, duration, and hardness are linked; correlations between these behaviors lead us to believe that most GRB pulses represent a single physical phenomenon. Pulses exhibiting possible exceptions to these behaviors are those that cannot be appropriately fit using these techniques. These pulses tend to fall into three categories: (1) pulses in crowded fields that cannot be unambiguously resolved (many have very short durations), (2) low signal-to-noise pulses that cannot be unambiguously resolved, and (3) bright yet uncommon pulses having shapes not adequately fitted by the four-parameter pulse model; when we are able to force a fit, we find these pulses to typically have short rise and very long decay times. We cannot ascertain whether there are systematic biases in pulse sampling, because we cannot know the properties of pulses we cannot measure. However, we note that we preferentially cannot fit pulses in complex GRBs, as these bursts by definition have many overlapping pulses.

Two key correlations are identified in a sample of 24 pulses from 13 BATSE bursts (Hakkila et al. 2008): (1) pulse amplitude (measured across BATSE’s four-channel energy range in units of counts s$^{-1}$) decreases with increasing lag (a Spearman rank-order correlation test indicates a probability of only 2.4 $\times$ 10$^{-4}$ that this correlation could occur randomly), and (2) pulse width w (measured across BATSE’s four-channel energy range) increases with increasing lag (the Spearman rank-order probability is 1.7 $\times$ 10$^{-3}$). It is remarkable that these correlations are robust enough to be clearly identified in the observer’s rather than in the GRB rest frame; intrinsic pulse properties (e.g., jet properties) must be significantly larger than extrinsic effects (e.g., cosmological redshift and the inverse square law) for this to be true. Short-lag pulses are brighter and shorter than long-lag pulses; this appears to be true both within bursts and from one burst to another.

To clarify what these relationships mean, we fit pulses of BATSE bursts with known redshift; these GRBs originally defined the lag versus peak luminosity relation (Norris et al. 2000). Some pulses in these GRBs cannot be fitted due to poor resolution and/or pulse overlap, so several complex GRBs have been limited to only one or two isolated pulses each. The resulting sample consists of 12 pulses in 7 bursts. Fitted peak fluxes have been recalibrated on the 256 ms timescale so that the results can be compared to those of Norris et al. (2000). The pulse peak lag, pulse duration, and pulse intensity have been corrected to the GRB rest frame. The pulse characteristics are plotted in Figures 2–4. Also plotted are pulses from BATSE GRBs without known redshifts, assuming $z = 1$. These pulses demonstrate (1) the pervasiveness of the correlations, and (2) the strength of these intrinsic relationships relative to cosmological effects.

Figure 2 demonstrates the pulse peak luminosity $L_{\text{p}}$ (the isotropic pulse peak luminosity $L$ in units of 10$^{51}$ erg s$^{-1}$) versus the rest-frame pulse peak lag $t_{\text{p}}$ (obtained by shifting $t_{\text{p}}$ into the rest frame); this is similar to the Norris et al. (2000) lag versus peak luminosity diagram, except that it has been applied to pulses rather than to the bursts themselves. The best-fit functional form of this relation (excluding underluminous GRB 980425) is $\log (L_{\text{p}}) = A + B \log (t_{\text{p}})$ (A is in units of 10$^{51}$ erg s$^{-1}$). An anticorrelated relationship (correlation coefficient $R = -0.72$) is identified, with $A = 0.54 \pm 0.05$ and $B = -0.62 \pm 0.04$. The validity of this relation for pulses both within and across GRBs implies that the pulse peak lag versus pulse peak luminosity relation is a fundamental one, while the CCF lag versus peak luminosity relation is of secondary importance. In fact, the two relationships have different power-law indices, with the lag versus peak luminosity relation’s power-law index being $B = -1.14 \pm 0.10$ (Norris et al. 2000). We have already demonstrated that the CCF lag is merely a rough measure of the narrowest pulse’s lag. Similarly, the peak flux is an overestimate of the narrowest pulse’s amplitude; peak flux results from summing fluxes from overlapping pulses, and Poisson errors also make the measured peak fluxes larger than the modeled fluxes (the “Meegan bias”).

Figure 3 plots the rest-frame pulse duration ($w_{\text{p}}$; given in units of s) versus pulse lag ($t_{\text{p}}$). Remarkably, the pulse duration versus pulse lag correlation holds over 4 orders of magnitude in both duration and lag; even the underluminous GRB 980425 follows it. Its functional form in the GRB rest frame is taken as $\log (w_{\text{p}}) = C + D \log (t_{\text{p}})$. From this small sample, the values of the coefficients are $C = 1.27 \pm 0.01$ s and $D = 0.85 \pm 0.01$, with $R = 0.95$.

The strong correlations in Figures 2 and 3 indicate that there must also be a pulse width versus pulse peak luminosity relation. Figure 4 demonstrates this relation, which is more tightly defined ($R = -0.88$) than the pulse peak lag versus pulse peak luminosity relation. Again, the exception to the rule is underluminous GRB 980425. The best-fit functional form of this
The short durations of most GRB pulses, along with the similar behaviors seen in these pulses, argue that most pulses are related to internal shocks rather than external shocks. Since most pulses do not seem to have external shock characteristics, we look elsewhere to find these pulses, e.g., to pulses that cannot be fitted easily using the pulse model. Although we cannot say anything about faint or overlapping pulses, we suggest that pulses with short rise and very long decay times might represent external shocks capable of initiating afterglow. Such pulses appear to have short lags, although they are often fitted by two overlapping pulses: one short, large-amplitude, short-lag pulse and one long, small-amplitude, indeterminate-lag pulse. Suggestive of these pulse types is the extended tail in GRB 980923 (Giblin et al. 1999), thought to occur at the transition from prompt emission to afterglow. We are exploring this hypothesis.

4. CONCLUSIONS

Multilag GRBs are ubiquitous—this Letter provides the first clear evidence in support of this statement. Each pulse appears to be characterized by its own lag; lag is a consequence of pulse evolution rather than a burst property. Burst peak luminosity and the CCF lag are not fundamental properties, but result from pulse combinations. Pulses are the basic, central building blocks of GRB prompt emission, and it is essential to our understanding of GRB physics that we properly catalog and characterize pulse properties.

Pulse lag, pulse luminosity, and pulse duration are strongly correlated, implying that most GRB pulses have similar physical mechanisms; these are more consistent with internal than external shocks. Short pulses presumably indicate a collision of material at larger relative Lorentz factor than long pulses, and a large Lorentz factor requires a cleaner fireball with less baryonic matter. The fireball opacity dictates the emission timescale, so a clean, high-amplitude fireball should have a short decay and a short lag, while a dirty, low-amplitude fireball should produce a long decay and a long lag.

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