1. INTRODUCTION

The occurrence of X-ray flares (XRFs) associated with a large percentage of the gamma-ray bursts (GRBs) detected by Swift is now well established (Burrows et al. 2005; Romano et al. 2006; Falcone et al. 2006; Chincarini et al. 2007). Interest now concentrates on how this flaring is related to the physics of the prompt emission, early afterglow, the transition between these phases via internal (and possible external) shock activities of GRBs, and the variability of the central engine itself (Rees & Meszaros 1994; Kobayashi et al. 1997; Panaitescu et al. 1999; Zhang et al. 2006; Maxham & Zhang 2009; Yu & Dai 2009). As has been noted in a number of studies (Burrows et al. 2005; Nousek et al. 2006; O’Brien et al. 2006; Willingale et al. 2007), the X-ray light curves observed by the Swift/X-Ray Telescope (XRT) follow a similar pattern; essentially comprised of a prompt exponential decay followed by a steep power-law decay over a certain timescale. For most GRBs, the steep decay is followed by a shallow plateau that gradually gives way to another decreasing phase during which the X-ray flux decays according to a different power law over a timescale that is significantly longer compared to the prompt emission and the early afterglow. XRFs are known to occur predominantly during the steeply declining phase of the X-ray light curve, but flares during the plateau portion of the light curve are not uncommon. Empirically, the behavior of the composite light curve is consistent with the presence of two emission processes that overlap in time (Willingale et al. 2007); a short-duration episode in addition to an episode longer in duration but lower in luminosity. However, the underlying mechanisms that produce the flaring activity are not fully understood. Typical questions that arise include: (1) are XRFs related to the late activity of the central engine, and (2) is the same (internal) shock mechanism responsible for both the prompt emission and the flaring activity? These questions have been tackled in different ways but focus primarily on linking the observed temporal and spectral properties of prompt emission in long bursts to similar properties seen in bursts exhibiting XRFs: examples of these properties and/or relations include extending the lag–luminosity relation to XRFs, comparing pulse profiles of temporal structures in the prompt emission and XRFs, and studies of evolution of spectral lag and the comparison of spectral hardness of XRFs with that of the underlying afterglow.

The lag–luminosity relation for XRFs has been investigated by Margutti et al. (2010) and was found to be consistent with the existing relation for the prompt emission (Ukwatta et al. 2012; Norris et al. 2005), suggesting that XRFs may share common origins with prompt emission. A very similar study (Sultana et al. 2012) makes a connection between the prompt emission data and the late afterglow X-ray data and suggests that the lag–luminosity relation is valid over a timescale well beyond the early steep-declining phase of the X-ray light curve. Maxham & Zhang (2009) present a summary of the salient properties of XRFs and also show, using an internal shell collision model, that the main time histories of XRFs can be explained by the late activity of the central engine. Another study that hints at a connection between the prompt emission and the X-ray afterglow is that of Kocevski et al. (2007) in which the authors examined the evolution of pulse widths of the flares and found that the correlation between the widths of the pulses and time is consistent with the effects of internal shocks at ever increasing collision radii. Other techniques that seem to hold promise include the study of $E_{\text{peak}}$ evolution (Sonbas et al. 2012), the investigation of the relations predicted by various curvature models (Liang et al. 2006; Shenoy et al. 2012), and the time variability of bursts.

In a recent wavelet analysis (MacLachlan et al. 2013) of the gamma-ray prompt emission from a sizable sample of long and short GRBs detected by the Fermi/Gamma-ray Burst Monitor (GBM) satellite, it was shown that a variability (related to the minimum timescale (MTS) that separates white noise from red noise) of a few milliseconds is quite common. Moreover, it was demonstrated that there is a direct link between the shortest pulse structures as determined by the MTS and pulse-fit parameters such as rise times. This type of analysis is quite easily extended to a larger sample of (long-duration) Swift bursts, where the time variability and pulse-fit parameters for both the prompt emission and XRFs can be extracted and compared. In this Letter, we report on the results of such an analysis.
2. DATA AND METHODOLOGY

The prompt emission light curves for a sample of GBM bursts were taken directly from the work of MacLachlan et al. (2013), who used a technique based on wavelets to determine the MTS at which scaling processes dominate over random noise processes. The authors associate this timescale with a transition from red-noise processes to parts of the power spectrum dominated by white-noise or random noise components. Accordingly, the authors note that this timescale is the shortest resolvable variability time for physical processes intrinsic to the GRB. We have used the same technique to extract the timescaling characteristics of the XRFs for a small sample of Swift bursts (see Table 1).

For the extraction of X-ray light curves, we used the method developed by Evans et al. (2009) in WT (windows timing) mode. Using the software tools available directly from their Web site (http://www.swift.ac.uk/user_objects/), we extracted XRF light curves with different time bins. By constructing log-scale diagrams (plot of log(variance) of the signal versus inverse frequency in octaves) for the sample, we have determined the MTS above which scaling processes dominate over random intrinsic noise processes. A typical example of a bright XRF light curve and the associated log-scale diagram is shown in Figure 1. Note that the white-noise region (the plateau region of the log-scale diagram) intersects the red-noise region (the scaling region) at around octave 3.5 which corresponds to approximately 6 s for the light curve in question. As noted by MacLachlan et al. (2013), the timescale for the transition from the scaling region to the plateau region provides a measure of the smallest time variation for physical processes intrinsic to the GRB. We associate this timescale with the variability of the burst.

Using a particular functional form for pulse shapes, Margutti et al. (2010) have extracted a set of key pulse-fit parameters such as rise times, decay times, widths, and times since trigger for a set of bright XRFs detected by Swift/XRT. Their prime interest lies in the testing of (and extending) the validity of the lag–luminosity relation for XRFs. Our immediate interest in this study, however, focuses on their results for the various pulse-fit parameters such as rise times and pulse widths, because we can use these directly to compare with the variability timescales that we have extracted for the prompt emission and the XRFs. We note that the pulse rise times are invariably shorter than the pulse widths or decay times. To augment our sample we have also used the pulse-fit parameters from the work by Kocevski et al. (2007). The appropriate pulse-fit parameters for the prompt emission data were taken from the catalog produced by Bhat et al. (2012).
Figure 2. Rise time vs. the minimum variability timescale in the observer frame for a sample of GRBs: black points (prompt emission); green and blue points (XRF data). The solid line indicates the equality of the respective temporal scales.

(A color version of this figure is available in the online journal.)

quantities because the redshift-dependent time dilation factor is the same for both variables: the black data points indicate the prompt emission data (with the pulse-fit parameters from Bhat et al. 2012); the blue and green points depict the XRF data with pulse-fit parameters taken from Kocevski et al. (2007) and Margutti et al. (2010), respectively. Also shown in the figure is a line depicting the equality of timescales. The best-fit line (not shown) leads to a slope of 1.26 ± 0.05. The data show a strong correlation (Spearman correlation of 0.96 ± 0.02 and a Kendall correlation of 0.79 ± 0.02) between pulse rise times and MTSs all the way from prompt emission to XRFs, i.e., more than three decades of variability time. This result extends the work of MacLachlan et al. (2012), who examined prompt emission only, to the temporal domain covered by XRFs and reinforces their main conclusion that the two techniques, wavelets and pulse fitting, can be used independently to extract an MTS for physical processes of interest as long as close attention is paid to time binning and the proper identification of distinct pulses. In order to pursue the apparent connection between the temporal properties of prompt emission and the XRFs, we explore below the possible link between another temporal property, that of spectral lags, and the MTS.

For the prompt emission data, we extracted spectral lags for various observer-frame energy bands using the CCF method described in detail by Ukwatta et al. (2012). Some of these results have been presented by Sonbas et al. (2012). Using the flare peak times reported by Margutti et al. (2010), we have also extracted the spectral lags for the XRFs between the energy bands 0.3–1 keV and the 3–10 keV, respectively. A plot of the spectral lags versus the MTS for the GRBs in our sample is shown in Figure 3. The black and magenta data points depict the prompt emission for long and short bursts; the blue points represent the XRF data. The red line indicates the best fit (a slope of 1.44 ± 0.07) through the combined data set. The results clearly indicate a strong positive correlation (a Spearman correlation of 0.96 ± 0.05 and a Kendall correlation of 0.86 ± 0.05) between the two temporal features, spectral lag, and the MTS. Also shown in Figure 3 (see insert) is a plot of the pulse rise times as function of the spectral lags. As expected, a positive correlation is observed but the scatter appears to be relatively large at the small timescales, possibly indicating the difficulty in the identification and fitting of pulses at these scales. In addition, we note, as did MacLachlan et al. (2012), that the uncertainties in the pulse rise times, quoted by Bhat et al. (2012), are in many cases significantly smaller than the time binning of the light curves. We follow MacLachlan et al. (2012) and adjust the uncertainties in the rise times by folding in quadrature the bin widths to the uncertainties given by Bhat et al. (2012). With this minor adjustment, we argue that the observed correlations, taken as a whole, are suggestive of more than a trivial connection between the prompt emission and the XRFs.

It is relatively straightforward to interpret the correlation between pulse parameters and the MTS in terms of the internal shock model in which the basic units of emission are assumed to be pulses that are produced via the collision of relativistic shells emitted by the central engine. Quilligan et al. (2002) in their study of the brightest BATSE bursts identified and fitted distinct pulses and showed a strong positive correlation between the number of pulses and the duration of the burst. More recent studies (Bhat & Guiriec 2011; Hakkila & Cumbee 2009; Hakkila & Preece 2011) have provided further evidence for the pulse paradigm view of the prompt emission in GRBs. Maxham & Zhang (2009) use the internal shell collision model to probe the spectral and temporal connection between the prompt emission and the XRFs. By assuming the Band function for the spectrum, an empirical temporal profile for the flares, and arbitrary central engine activity, they are able to explain the major temporal features of the XRFs, in particular, they note that the XRF time history reflects the time history of the central engine, which reactivates multiple times after the main prompt emission phase. Other authors (Narayan & Kumar 2009) invoke relativistic outflow mechanisms to suggest that local turbulence amplified through Lorentz boosting leads to causally disconnected regions that in turn act as independent centers for the observed prompt emission. In more recent developments (Zhang & Yan 2011; Vetere et al. 2006; Gao et al. 2012; MacLachlan et al. 2013),
there is a suggestion that the variability may be composed of two distinct timescales; a rapidly varying component (of the order of milliseconds) embedded on a slower component (of the order of seconds) with the implication that these two components probe distinctly different aspects of GRB production and propagation. Similarly, simulation studies (Morsony et al. 2010) of the propagation of a jet through stellar material indicate that the temporal variability at different timescales is possibly related to the central engine and the propagation of the jet itself, and is measurable from the prompt emission. In the model reported by Zhang & Yan (2011), the authors invoke a magnetically dominated relativistic outflow to suggest that it is the slow component of the variability that is linked to the activity of the central engine and that the more rapidly varying component is associated with magnetic turbulence. While we are not in a position to distinguish between the aforementioned models, which incidentally are typically used to describe the variability only in the prompt emission, it is intriguing nonetheless that the observed correlation particularly that between the spectral lag and the MTS connects both the prompt emission and the flaring activity.

Kocevski et al. (2007) suggest that the rise time of the XRF pulse is related to the shell thickness as two shells collide after the second (faster) shell catches up with the (slower) first shell. The observed rise time is estimated by $\Delta t_r \approx (\delta R/2c\Gamma_m^2)$, where $\delta R$ is the thickness and $\Gamma_m$ is the relative Lorentz factor of the merged shells. Higher-latitude emission (for viewing angles less than the opening angle, $\theta$, of a conical jet) will be detected as broader pulses than lower-latitude ones. Following Zhang et al. (2006), one can determine the decay timescale as the difference in light-travel time between photons emitted along the line of sight and the photons emitted at an angle along a shell of a given radius, $R$:

$$\Delta t_{\text{decay}} \approx (R/c)(\theta^2/2).$$

For simplicity, we have omitted the redshift-dependent dilation factor. If we can assume the decay timescale is the spectral lag due to curvature, then the above arguments suggest a correlation between the lag and some measure of the variability which we associate with the MTS. While our interpretation is obviously speculative, the existence of the strong correlation, which we contend to be of astrophysical significance, warrants detailed theoretical investigation.

As far as the extraction of the time variability directly from data is concerned, the wavelet method of MacLachlan et al. (2013) does not assume any temporal profile nor does it rely on identifying distinct pulses but instead uses the multi-resolution capacity of the wavelet technique to resolve the smallest significant temporal scale present in the light curves (of prompt emission and XRFs). These authors showed that the shortest pulse structures and the MTS track each other very closely for the prompt emission. In this work we have demonstrated that the spectral lag too tracks the MTS. Moreover, we have extended the work of MacLachlan et al. (2012) to include both the prompt emission and the XRFs. This result, depicted in Figure 3 (supported by the data in Figure 2), provides new and compelling evidence that, as far as these temporal measures are concerned, the XRFs appear to be simple “temporal extensions” of the pulse structures observed in the prompt emission.

4. CONCLUSIONS

For a sample of long-duration GRBs detected by the Fermi/GBM and Swift missions, we have extracted the minimum variability timescales and spectral lags for both prompt emission and XRF light curves. In addition, we have utilized the pulse-fit parameters presented by Margutti et al. (2010) and Kocevski et al. (2007) from their respective studies of XRFs. We compare the minimum variability timescale, extracted through a technique based on wavelets, both with the pulse rise times extracted through a fitting procedure, and spectral lags extracted...
via the CCF method. With these combined results, we have studied the relationship between key parameters that describe the temporal properties of a sample of prompt emission and XRF light curves. Our main results are summarized as follows: (1) the prompt emission and the XRFs exhibit a significant positive correlation between pulse rise times and the MTS, with timescales ranging from several milliseconds to a few seconds, respectively; (2) the short-time variabilities in the prompt emission scale over time into the short-time variabilities in XRFs; and (3) the spectral lag for both the prompt emission and the XRFs shows a strong positive correlation with the minimum variability timescale. Taken together, these results are highly suggestive of a direct link between the mechanisms that lead to the production of XRFs and prompt emission in GRBs.

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