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Spectral Lags and Characteristic Time Scales of GRBs with Known Redshift

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Abstract − In this study, we extracted two key prompt emission parameters, i.e., spectral lags and characteristic time scales, and investigated their potential correlation. The minimum variability time scale (MTS) was determined using a wavelet-based method, while spectral lag analysis was conducted via the cross-correlation function (CCF) to examine the temporal properties of 162 gamma-ray bursts (GRBs) with known redshifts observed by the Swift/BAT satellite between 2011 and 2019. The analysis suggests short-duration bursts exhibit a shorter variability time scale than long-duration bursts. Although the MTS value for most long- and short-duration GRBs is shorter than T_{90}, a few cases approach the equality limit. Additionally, long-duration bursts tend to have a higher spectral lag than short-duration bursts. We found spectral lag values consistent with zero within their uncertainties for short-duration GRBs. Spectral lags exhibit a strong positive correlation with MTS and a negative correlation with the isotropic peak luminosity (L_{iso}), with slopes of 1.01 ± 0.04 and -1.13 ± 0.20, respectively.

Keywords − *Gamma-ray burst, minimum variability time scale, spectral lag, wavelet, cross-correlation function*

1. Introduction

Gamma-ray bursts are among the most luminous phenomena in the universe. They emit enormous amounts of energy as gamma rays, ranging from 10^{49} to 10^{54} ergs, over a few milliseconds to several minutes. These unpredictable events occur, on average, a few times per day, emitting in random directions at cosmological distances. Their duration ranges from milliseconds to several thousand seconds [1].

The prompt emission of GRBs is well described by the fireball model, in which relativistic shells are ejected from a central engine. These shells collide shortly after being ejected, creating internal shocks that generate prompt emissions [1]. The light curves of prompt emission exhibit irregular, non-periodic peaks that vary significantly from burst to burst [2].

GRBs are classified into two main categories: long-duration and short-duration bursts, based on their T_{90} durations [3]. The T_{90} parameter refers to the time interval during which 90% of the total fluence of the burst is detected. Long-duration GRBs (T_{90} ≥2 seconds) are associated with the core collapse of massive stars. In contrast, short-duration GRBs (T_{90} < 2 s) originate from compact binary mergers, such as neutron star-neutron star (NS-NS) or neutron star-black hole (NS-BH) mergers [4].

The prompt emission of GRBs shows complex temporal profiles, with rapid variability often occurring on sub-millisecond timescales. Understanding these rapid variations is crucial for probing the underlying physical processes of GRBs and their origins [5-8]. The study of variability patterns in GRBs provides valuable insights

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into the structure, emission mechanisms, and spatial extent of the source region, shedding light on the physics of the central engine. Variability on timescales ranging from milliseconds to seconds, believed to arise from internal shocks, offers crucial constraints on the size, location, and physical properties of the emission region, making it a key diagnostic tool for investigating GRB prompt emissions and constraining theoretical models [9, 10].

As noted in previous studies, the observed correlation between temporal variability and isotropic peak luminosity suggests that the temporal characteristics of prompt emission light curves offer insights into the microphysics governing GRB emission [11, 12]. The internal shock [10] and photospheric [13] models propose that rapid variability is directly linked to central engine activity, reinforcing the role of temporal analysis in understanding relativistic jet dynamics**.**

In [8], the wavelet technique was applied to extract the MTS from a sample of long and short GRBs observed by Fermi/GBM. The results showed that the MTS of long GRBs differs significantly from that of short GRBs and that a correlation exists between MTS and T_{90}**.** Similarly, [14] extracted MTS for both prompt emission and X-ray flares from GRBs observed by Fermi and Swift, revealing that X-ray flares and prompt emission may share a common origin. Additionally, [15] reported a correlation between MTS and the bulk Lorentz factor of GRB outflows. Moreover, a correlation was noted between the timescales of afterglow and prompt emission variability with the peak times of the bursts.

Spectral lags, the time delay between high- and low-energy photons, serve as a key parameter in distinguishing emission mechanisms and constraining the geometry and kinematics of the emitting regions [10, 11]. The study of these lags has been crucial for understanding GRB emission processes. In the literature, an anti-correlation between spectral lag and isotropic peak luminosity is also reported, an important feature that aids in differentiating emission models [16-20]. In a recent study [18], deriving a slope of -1.2 ± 0.2 from GRB datasets with known redshifts observed by Swift/BAT. These studies are particularly relevant for short GRBs, where the spectral lag distribution differs from that of long GRBs.

In this study, we extracted spectral lags in the source frame and the MTS in both the observer and source frames for a sample of long- and short-duration GRBs observed by Swift/BAT. The structure of this article is as follows: Section 2 describes the methodology, Section 3 presents the main results, and Section 4 concludes with a discussion of our findings.

2. Materials and Methods

The prompt emission light curves of 162 long- and short-duration GRBs with known redshifts, observed by the Swift/BAT satellite between 2011 and 2019, were generated and examined to investigate their temporal properties. The data utilized in this study were obtained from the Swift archives [21]. The mask-weighted and background-subtracted light curves were generated using HEASOFT and the software tools available for Swift/BAT.

Examining the variability of both short and long GRBs is crucial for better understanding their emission properties and for testing key components in various models. The MTS, defined as the intersection of the white noise (background) and the red noise component containing the GRB signal, is calculated using the wavelet technique [8]. Light curves with a time bin of 200μs were generated within the standard Swift energy bands of 15–150 keV. Log-scale diagrams for each GRB were then created to identify white and red noise regions. Finally, the intersection of the scaling region and the flat portion in the log-scale diagram was extracted as the MTS [22].

Spectral lag indicates the time delay between the arrival of high-energy and low-energy photons. A positive spectral lag is observed when higher-energy photons arrive before lower-energy photons. A modified CCF method was used to calculate the spectral lag in the source frame and its related uncertainty [17, 22]. Due to the redshift dependence, the spectral lag between two arbitrary energy bands in the observer frame may correspond to a different pair of energy bands in the GRB's source frame. This redshift dependence could result in an energy-dependent spectral lag. Therefore, it is recommended to calculate spectral lags in the source frame rather than in the observer frame [18, 23]. To extract the source frame lags, the standard energy bands of 100–150 keV and 200–250 keV were chosen in the source frame. Then, the light curves were created at different time resolutions for each GRB with known redshift by dividing by the factor of (1+z).

3. Results and Discussion

This study calculated spectral lag and MTS from the prompt emission light curves of 162 GRBs, including eight short-duration and 154 long-duration GRBs, observed by the Neil Gehrels Swift Observatory between 2011 and 2019. The MTS was determined using the wavelet technique, and the results are summarized in Figures 1 and 2 for the observer and source frames, respectively.

The obtained MTS values are compared with those from [8] in the observer frame (Figure 1), consistent with their findings, which show a clear temporal separation between short and long GRBs. Similarly, the source frame distribution shows that short-duration GRBs have smaller MTS values than long-duration bursts. This finding supports the hypothesis that the emission mechanisms or progenitor systems for short-duration and long-duration GRBs may differ, further highlighting the distinct nature of these two GRB classes.

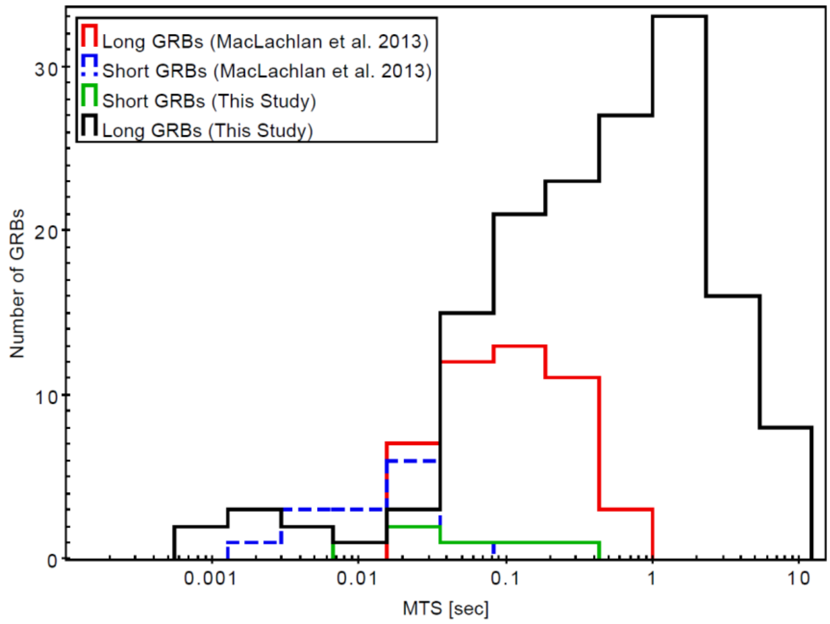

Figure 1. A histogram of MTS, in the observer frame, of long and short-duration GRBs, compared with the previous results of [8]

Similarly, the distribution of MTS values was also examined in the source frame, and the results are presented in Figure 2. To clearly illustrate the difference between the two distributions, the vertical axis of the histogram was randomly normalized. The source frame distribution of MTS values, as in the observer frame, shows that short-duration GRBs have smaller values than long-duration GRBs in both the source and observer frames. This observation is consistent with previous studies [8], which suggest that the shorter timescales in short GRBs may result from their distinct progenitors or more energetic central engines, leading to a faster release of energy.

Additionally, the correlation between MTS and burst duration (T_{90}) was analyzed in both the observer frame (Figure 3) and the source frame (Figure 4). Red circles represent long GRBs, while blue triangles mark short GRBs. These figures illustrate that the data points mostly fall below the MTS-T_{90} equality line (dashed line), indicating that MTS values are generally smaller than T_{90}. Short GRBs, in particular, exhibit smaller MTS values compared to long GRBs. The MTS-T_{90} correlation plane shows a relatively tight clustering of long- and short-duration GRBs. This observed clustering suggests a well-defined correlation between variability timescales and burst durations across GRB types. Moreover, the findings obtained from approximately 8 years of data are consistent with those reported by [8] in both the observer and source frames. While [8] analyzed a sample of 60 GRBs (14 short-duration and 46 long-duration), our study examines 164 GRBs (8 short-duration and 156 long-duration). Despite the difference in sample size, the trends observed in both datasets align well, particularly in the MTS distributions, with similar patterns in both the observer and source frames (Figures 3 and 4) compared to their work (Figures 5 and 6).

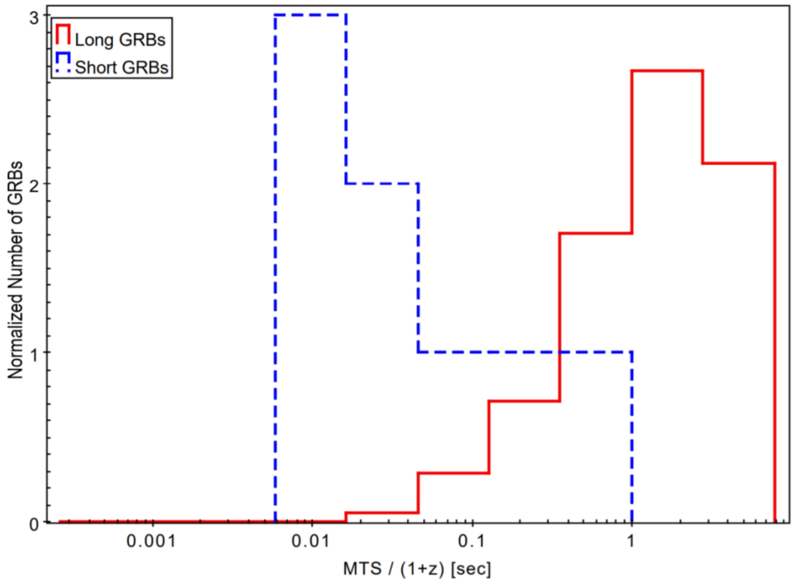

Figure 2. A histogram of MTS, in the source frame, of long-duration (red) and short-duration (blue) GRBs

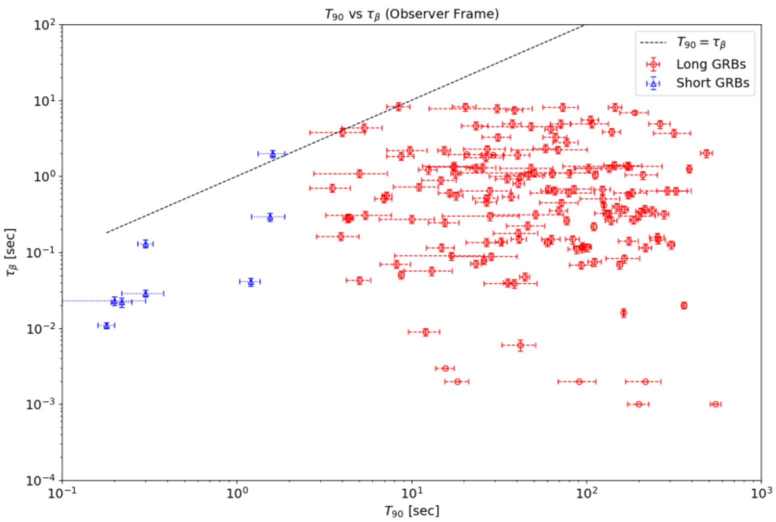

Figure 3. MTS versus T_{90} in the observer frame (red circles: long-duration GRBs, blue triangle: short-duration GRBs). The path of MTS (τ_β) equal to T_{90} is also shown (as a dashed line)

We examined the spectral lag-luminosity correlation for short-duration GRBs by calculating spectral lags from the light curves. The results show that the spectral lag values for short-duration GRBs are consistent with zero, indicating no significant time delay between high-energy and low-energy photons. This finding suggests that short-duration GRBs do not exhibit temporal separation in their emission and may be governed by a different mechanism than long-duration GRBs [11, 17, 18]. Further details on these calculations and methods can be found in [22].

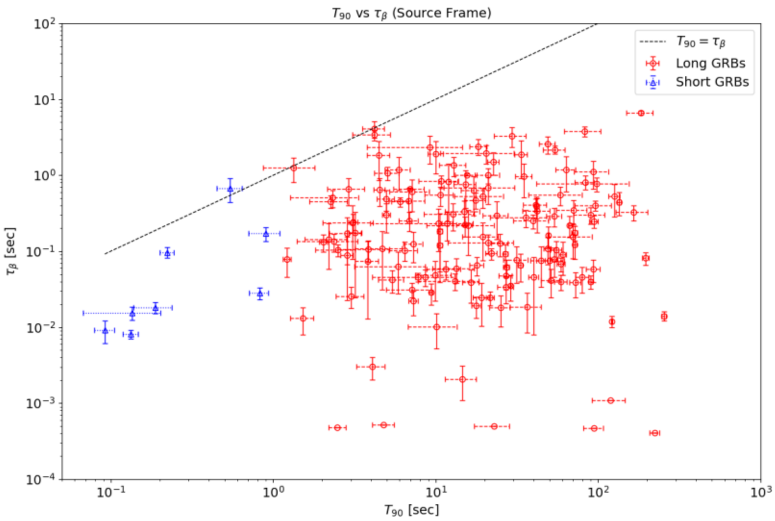

Figure 4. MTS versus T_{90} in the source frame (red circles: long-duration GRBs, blue triangle: short-duration GRBs). The path of MTS (τ_β) equal to T_{90} is also shown (as a dashed line)

For the 25 GRBs with positive spectral lag values and known isotropic peak luminosity measurements, the correlation between redshift-corrected spectral lag and isotropic peak luminosity was modeled using a best-fitting power-law curve, following the method used by [17, 18]. Figure 5 shows the isotropic peak luminosity as a function of redshift-corrected spectral lag for these bursts, directly comparing the two parameters. The best-fit power-law curve yields a slope of −1.13 ± 0.20, which is consistent with the indices of −1.2 ± 0.2 and −1.14 reported by [18] and [20], respectively, as well as with the average power-law index of −1.4 ± 0.3 reported by [17]. This consistency supports the robustness of the correlation between luminosity and spectral lag, further highlighting the significance of these parameters in GRB studies.

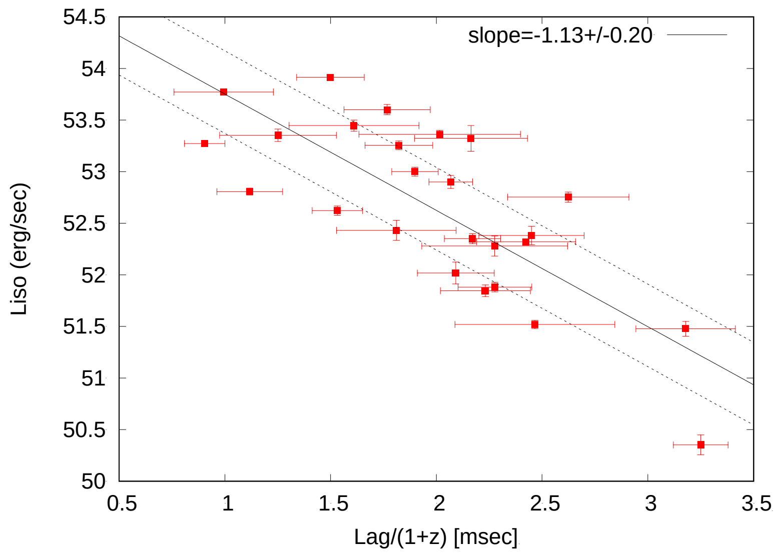

Figure 5. The spectral lags between the source-frame energy range bands 100–150 and 200–250 keV and the isotropic peak luminosity are plotted in a log-log plot. Here, the solid black line shows the best-fitting power-law curve and 1 sigma dispersion curves

Comparing the MTS and spectral lag is critical for understanding the underlying mechanisms of GRB prompt emission. A correlation between these parameters is expected if the curvature effect is the dominant mechanism responsible for spectral lags. The curvature effect arises from the observer viewing radiation from increasingly off-axis regions of an expanding, curved shell, where photons from off-axis areas experience a smaller Doppler boost and longer light-travel times, leading to a delay in lower-energy emission [14,18]. Our analysis reveals a strong positive correlation between spectral lag and MTS, as shown in Figure 6. The best-fit line, represented by the red solid line, has a slope of 1.01 ± 0.04. This strong correlation suggests that the curvature effect may significantly contribute to the observed spectral lags, and it necessitates further theoretical investigation to elucidate its physical origin and implications.

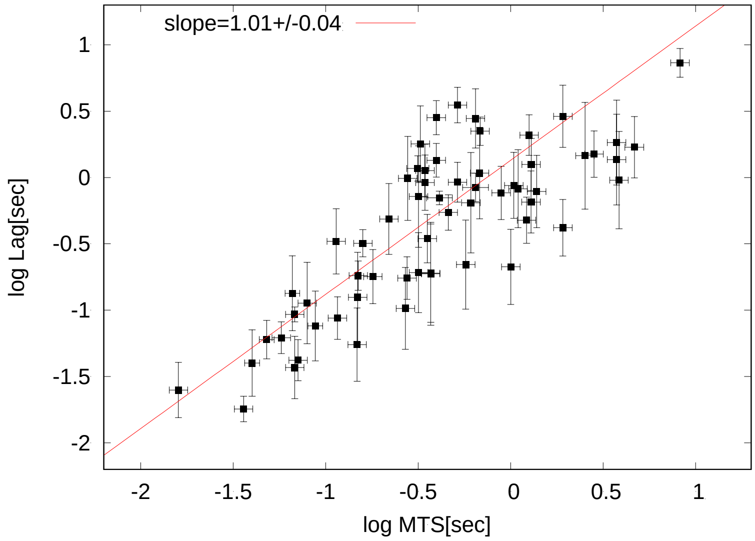

Figure 6. Correlation between spectral lag and MTS for GRB prompt emission

These results contribute to understanding GRB variability and emission mechanisms by providing a detailed correlation analysis between temporal parameters like MTS and spectral lag. The consistency of our findings with previous studies reinforces the validity of these results and emphasizes the importance of these parameters in characterizing GRBs. This work adds to the growing body of evidence supporting the utility of MTS and spectral lag as diagnostic tools for exploring the physics of GRBs.

4. Conclusion

In this study, we extracted the MTS and spectral lags from the prompt emission of 162 short- and long-duration GRBs observed by the Swift/BAT with known redshift values. The MTS was obtained using a wavelet-based technique, while spectral lags were derived using the cross-correlation function. A comparison between MTS and spectral lag was conducted to investigate their correlation. The key findings of our study are summarized as follows:

i. Short-duration bursts exhibit smaller MTS values than long-duration bursts, as observed in both the source and observer frames.

ii. MTS >1 s was obtained for some of the long-duration GRBs.

iii. A distinct temporal difference between long and short-duration GRBs is evident, as discussed in [8].

iv. Long-duration GRBs show significant spectral lags, while short-duration bursts have spectral lags consistent with zero, in agreement with the findings of [20, 24].

v. The Lag–L_{iso} correlation exhibits a strong relation with a slope of −1.13±0.20, consistent with earlier studies [17,18, 20].

vi. A strong correlation (1.01±0.04) between spectral lag and MTS warrants a detailed theoretical investigation.

The study of variability patterns provides crucial insights into the size and location of the GRB source region, which is essential for understanding the emission mechanisms driving these energetic events [10]. Our analysis of spectral lag and MTS in long- and short-duration GRBs reveals distinct variability characteristics that reflect differences in their underlying physical processes. The strong correlation between spectral lag and MTS suggests a fundamental connection between the two parameters, potentially linked to emission mechanisms such as the curvature effect or jet evolution. The significant spectral lags and larger MTS values in long-duration GRBs indicate a more complex emission process, possibly driven by an evolving jet or multiple emission regions. Conversely, the smaller spectral lags and shorter MTS in short-duration GRBs suggest a more compact or uniform emission mechanism consistent with models of compact binary mergers. These findings highlight the importance of variability studies in distinguishing between different GRB progenitors and emission scenarios [11, 19].

The MTS values greater than 1 s are particularly significant as they imply a more complex emission process, potentially driven by an evolving jet or multiple emission regions. This is consistent with the idea that variability in the emission can help determine the size and location of the GRB source region. In the context of the internal shock model, such MTS values are physically relevant since the dissipation radius (r) is proportional to the square of the Lorentz factor (Γ) and the variability timescale (δt), with $r \sim \Gamma^2 c\, \delta t$. Therefore, understanding δt is crucial for calculating the dissipation radius. Furthermore, MTS > 1 s values are also crucial in the study of low-luminosity GRBs. Understanding how variability scales in these bursts can provide additional insight into the nature of their central engines and the dynamics of their jets [25-27].

Future studies should explore the physical mechanisms underlying the observed correlations, particularly the interplay between spectral lag, MTS, and GRB central engines. Investigating the effects of redshift and energy dependence on these parameters will further refine our understanding of GRB emission processes. Additionally, theoretical models explaining these correlations need to be improved, and more observational data are required to validate and extend these findings across a broader range of GRBs. As spectral lags are crucial for understanding the emission mechanisms, continued studies on variability and spectral lags—particularly in short-duration GRBs—will provide deeper insights into the activity of the central engine and the physical conditions during the prompt emission phase.

Author Contributions

All the authors equally contributed to this work. This paper is derived from the first author's master's thesis supervised by the second author and co-supervised by the third. All authors have read and approved the final version of the paper.

Conflicts of Interest

The authors report no conflicts of interest.

Ethical Review and Approval

Approval from the Board of Ethics is not required.

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