AN INTRINSIC CORRELATION BETWEEN GRB OPTICAL/UV AFTERGLOW BRIGHTNESS AND DECAY RATE

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Abstract. We examine 48 *Swift*/UVOT long Gamma-ray Burst light curves and find a correlation between the logarithmic luminosity at 200 s and average decay rate determined from 200 s onwards, with a Spearman rank coefficient of -0.58 at a significance of 99.998% (4.2σ). We determine the $\log L_{200\text{s}} - \alpha_{>200\text{s}}$ correlation to be intrinsic and discuss two possible causes: there is a property of the central engine, outflow or external medium that effects the rate of energy release so that the bright afterglows release their energy more quickly and decay faster than the fainter afterglows; alternatively, the observers viewing angle may produce the correlation, with observers at large viewing angles observing fainter and slower decaying light curves.

1 Introduction

In 2009, we analyzed a sample of 26 optical long Gamma-Ray Burst (LGRB) light curves (Oates *et al.* 2009), unearthing a correlation between the observed v -band magnitude at 400 s and the average UVOT light curve decay rate determined from 500 s. In order to have implications on our understanding of LGRBs this correlation must be observed in the rest frame, however due to the small sample size we could not confirm or exclude a correlation. Here we use a larger sample of

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Fig. 1. Optical luminosity light curves of 56 LGRBs at restframe 1600 Å. For clarity, 3σ upper limits are not included.

48 high quality LGRB UVOT light curves to re-examine if there is a correlation between optical/UV afterglow intrinsic brightness and light curve decay rate.

2 Luminosity light curves

We selected 69 LGRBs from the second *Swift* UVOT GRB afterglow catalogue (Roming *et al.* 2013) using the criteria in Oates *et al.* (2009): the light curves must have a peak UVOT v -band magnitude brighter than 17.89, UVOT must observe from ≤ 400 to $\geq 10^5$ s after the BAT trigger and the colour of the afterglows must not evolve significantly with time, so that at no stage should the light curve from a single filter significantly deviate from any other filter light curve when normalized to the v filter. These ensure a high signal-to-noise light curve, covering both early and late times, can be constructed from the UVOT multi-filter observations using the method in Oates *et al.* (2009). The main steps were to normalize the multi-filter light curves to the v filter and then group them using a binsize of $\Delta t/t = 0.2$.

Of the 69 GRBs, luminosity light curves could be produced for the 56 that had redshifts and for which host $E(B-V)$ values could be determined. For each of the 56 GRBs, the single filter count rate light curves were converted to luminosity at a common restframe wavelength of 1600 Å, and were corrected for both Galactic and host extinction.

3 Results

The luminosity light curves at 1600 Å, given in Figure 1 with units of $\text{erg s}^{-1} \text{Hz}^{-1}$, are clustered in a single group, with the largest range in luminosity at the earliest epochs, which becomes narrower as the light curves decay. This suggests that the most luminous GRBs decay the quickest, while the less luminous GRBs decay

Fig. 2. Average decay index determined from the luminosity light curves after 200 s *versus* luminosity at 200 s. The blue solid line represents the best fit regression, $\log L_{200\text{s}} = (-3.636 \pm 0.004)\alpha + (28.08 \pm 0.13)$, and the green dashed lines represents the 3σ deviation.

more slowly. To verify this observation, we performed a Spearman Rank test on the logarithmic luminosity, $\log L_{200\text{s}}$, interpolated at 200 s using the data between 100 and 2000 s, and the average decay rate $\alpha_{>200\text{s}}$, determined by fitting a single power law to the light curves from 200 s onwards. We chose a restframe time of 200 s as all the light curves in the sample have observations by this time. For the 48 GRBs, for which we could determine $\log L_{200\text{s}}$ and $\alpha_{>200\text{s}}$ (see Fig. 2), a Spearman rank test gives a coefficient of -0.58 at a significance of 99.998% (4.2σ), confirming that luminous optical/UV afterglows decay quicker than less luminous ones.

To exclude the possibility that the correlation results from both parameters being related to redshift, we determined the partial Spearman rank correlation. This measures the degree of correlation between two parameters, excluding the effect of a third (see Kendall & Stuart 1979). This results in a coefficient of -0.50 with a confidence of 99.97% (3.5σ), and indicates that the $L_{200\text{s}} - \alpha_{>200\text{s}}$ correlation is not a result of the implicit correlation between these two parameters and redshift.

We also examined if the correlation was a result of the selection criteria or due to chance by performing a Monte Carlo simulation using 10^6 trials. For each trial, we simulated a random distribution of 48 pairs of $\log L_{200\text{s}}$ and $\alpha_{>200\text{s}}$. For each pair, we calculated the observed frame light curve, using the values of $\log L_{200\text{s}}$ and $\alpha_{>200\text{s}}$, and randomized parameters for redshift, extinction and k-correction. If the resulting observed frame light curve did not meet our selection criteria we discarded the $\log L_{200\text{s}} - \alpha_{>200\text{s}}$ data point from the simulated distribution and drew a new pair of values until the selection criteria was met. Once 48 valid pairs had been verified, we ran a Spearman Rank correlation on the distribution.

Of the 10^6 trials, only 34 have a correlation coefficient equal to or indicating a stronger correlation than the real $L_{200\text{s}} - \alpha_{>200\text{s}}$ distribution. Therefore at 4.1σ

confidence, the $L_{200s} - \alpha_{>200s}$ correlation is not due to our selection criteria or by chance and implies that the $L_{200s} - \alpha_{>200s}$ correlation is intrinsic to LGRBs.

4 Discussion

We shall now examine 3 ways to produce a $\log L_{200s}$ and $\alpha_{>200s}$ correlation.

4.1 Basic GRB afterglow model

A correlation between $\log L_{200s}$ and $\alpha_{>200s}$ may be a natural result of the jet interacting with the external medium producing synchrotron emission, which results in a relationship $L \propto t^\alpha \nu^\beta$, where β is the spectral index, and, α and β are linearly related by the standard set of closure relations (*e.g.* Zhang *et al.* 2006). There are two scenarios that could produce the $\log L_{200s} - \alpha_{>200s}$ correlation. In the simplest scenario, the optical light curves, for all GRBs, are produced from the same spectral regime and therefore are produced from the same spectral segment and have the same density profile. A single closure relation would describe the relationship between α and β and we should expect a correlation between these two parameters and a correlation between $\log L_{200s}$ and β . However, we can exclude this scenario as we do not observe either of these correlations in Figure 3. In the second scenario, we consider the optical afterglows to be produced by multiple spectral regimes. In Figure 3 we display the closure relations for three most likely spectral regimes. In this more complex scenario, we should expect to see clustering of the luminosities around a given closure relation, but again we do not observe this in Figure 3. We thus exclude a basic standard afterglow model as the cause of the correlation.

4.2 Complex GRB afterglow model

There may be an additional mechanism or parameter in the standard model that regulates energy release in GRB afterglows, depending on the rate of decay, such that if the energy is released quickly the result is a bright-fast decaying afterglow, while if the energy is released more slowly a fainter-slower decaying afterglow is observed. One possibility could be continued energy injection. For instance, if the central engine does not release its energy all in one go, but releases it over a much longer duration, then we may expect faint - slowly decaying afterglow.

4.3 Off-axis and structured outflows

The $L_{200s} - \alpha_{>200s}$ correlation may instead be a geometric effect resulting from a range in viewing angle, θ_{obs} . The faint-slowly decaying optical afterglows would be those observed at the largest angles, while the bright-fast decaying light curves would be observed within the outflow (see Fig. 3 of Panaitescu & Vestrand 2008). If the outflow is also structured, the result is similar, but the convergence time

Fig. 3. Optical/UV temporal and spectral indices for the 48 GRBs. The lines represent 3 closure relations and a colour scale is used for the range in luminosity at 200 s, $\log L_{200s}$.

and the range of light curve decays will vary, depending on the energy distribution within the jet.

5 Conclusions

We find an intrinsic correlation between optical/UV luminosity at 200 s and average decay rate determined from 200 s onwards with a significance of 99.998% (4.2σ). We give two possible causes: an intrinsic mechanism or physical quantity that controls how quickly the energy is released, such that bright, fast-decaying afterglows release their energy more quickly than faint, slow-decaying afterglows; alternatively, the observers viewing angle may produce the correlation, with observers at large viewing angles observing fainter and slower decaying light curves.

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