Are GRB optical afterglows relatively brighter at high z?

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ABSTRACT
The redshift distribution of gamma-ray bursts (GRBs) is strongly biased by selection effects. We investigate, via Monte Carlo simulations, one possible selection effect that may be modifying the Swift GRB redshift distribution. We show how telescope response times to acquire a GRB redshift may, via the Malmquist effect and GRB optical afterglow (OA) brightness distribution, introduce a bias into the average of the observed redshift distribution. It is difficult to reconcile a recently reported correlated trend between telescope response time and average redshifts unless we employ a redshift-dependent OA distribution. Simulations of this selection effect suggest that GRB OAs may have been either intrinsically brighter early in the Universe or suffered less local host galaxy extinction.

Key words: gamma-rays: bursts.

1 INTRODUCTION
The NASA Swift satellite, launched in 2004 November, heralded a new era of rapid gamma-ray burst (GRB) localization. X-ray and ultraviolet telescopes on board Swift provided the means to localize GRBs with small error boxes, so that dedicated ground-based telescopes could image the fading optical afterglow (OA). Interestingly, only about 50 per cent of localized GRBs were identified with an OA prior to Swift. Swift’s sensitivity, combined with the growing number of rapid response ground-based telescopes capable of spectroscopy, promised to fill the gaps of GRB redshifts. Surprisingly, this did not happen: optical/NIR afterglows have been found for nearly 80 per cent of GRBs but only 40–50 per cent have measured redshifts (Tanvir & Jakobsson 2007). Nevertheless, the synergy between Swift’s sensitivity and localization capabilities and the growing number of rapid response ground-based telescopes has greatly improved the number of GRB redshifts that could be determined.

2 GRB REDSHIFT SELECTION EFFECTS
The probability of GRB redshift measurement is proportional to the signal-to-noise ratio of the absorption or emission lines of the OA. Usually, multiple prominent lines are required, but this condition is hampered because GRB OA brightness decays roughly as $1/t$. In addition, many GRB host galaxies are too faint for redshifts to be obtained, so that the time taken to image and acquire spectra becomes critical. This was first pointed out by Fiore et al. (2007) for the observed discrepancy between the HETE and BeppoSAX redshift distributions compared to Swift. Coward (2009) showed that the time taken to acquire a redshift measurement has led to a selection effect that is biasing the Swift redshift distribution.

Coward (2007) and Coward et al. (2008) showed that for $z \approx 0–1$, the GRB redshift distribution should increase rapidly because of increasing differential volume sizes and strong SFR evolution. Until mid-2007, this characteristic in the Swift redshift distribution was not apparent. To account for this discrepancy, they argue that other biases, independent of the Swift sensitivity, are required. The lack of measured redshifts for $z \approx 1–2$ up to mid-2007, discussed by Coward et al. (2008), is at least partially explained by selection effects from ground-based optical telescopes.

2.1 GRB redshifts and their statistics
A shift of the mean of the GRB redshift distribution was observed in the early part of the Swift mission (Berger et al. 2005). This was attributed to the improved sensitivity and more accurate localization by Swift, resulting in a bias for fainter and higher redshift bursts. Jakobsson et al. (2006) showed that within the first year of Swift the mean redshift for a subset of 28 bursts had increased to approximately 2.8, about double that of the pre-Swift average redshift.

Assuming that satellite sensitivity is the dominant factor for determining redshift statistics, one could assume that the high mean redshift observed in the early part of the mission would remain fairly constant. If other factors impact on the statistics, such as the time taken to acquire high signal-to-noise spectra, the statistics may well reflect this. Assuming that Swift’s sensitivity and GRB localization ability has not degraded over time, one must consider the next link in the chain for measuring GRB redshifts: optical follow up by telescopes capable of spectroscopy.

This basic idea can be related to GRB optical follow-up in terms of the efficiency of localizing, imaging and obtaining high-quality spectra suitable for measuring redshift. In particular, a critical factor...
that determines the efficiency of these tasks is the time it takes to localize the rapidly fading OA and to obtain high signal-to-noise spectroscopy.

A downward drift in the Swift GRB mean redshift has been reported by Burrows (2008), and is reflected in the updated sample of Jakobsson et al. (2006) (http://www.raunvis.hi.is/~pja/GRBsample.html). The Swift team recently confirmed that this bias is not due to the satellite triggering algorithms (Osborne, private communication). Recently, Coward (2009) has indicated that the source of this bias is most likely a selection effect from the improvement over time of the ground-based telescope efficiency to obtain spectroscopic redshifts. This results in decreasing telescope response times, $T_z$. The intriguing result from this study is the decrease in average redshift, $\langle z \rangle$, of the bursts with decreasing average response time, $\langle T_z \rangle$, illustrated in Fig. 1. This is the opposite of what one would expect for a brightness-dependent bias. To understand this relationship, one must consider how $\langle z \rangle$ is modified by the magnitude limit of a telescope and the brightness distribution of the OAs.

The observation by any magnitude-limited telescope of the OA events described above is subject to a familiar selection effect called the Malmquist bias (Teerikorpi 1997; Butkevich, Berdyugin & Teerikorpi 2005). This bias results from the preferential selection of intrinsically brighter members of a particular source luminosity distribution as their distance increases. This bias occurs whatever the luminosity distribution of the sources.

3 SIMULATING A TELESCOPE-DEPENDENT REDSHIFT DISTRIBUTION

The aim of this paper is restricted to identifying possible reasons for the positive correlated trend in the observed data shown in Fig. 1. To do this, we build a simple Monte Carlo model of OAs to study the effect of varying telescope response times. The model serves as an exploratory tool to enable a semi-quantitative study of the unexpected nature of the $(T_z)-\langle z \rangle$ relation reported above.

Two probability density functions (pdfs) are central to this model: the first is the OA luminosity distribution (i.e. normalized luminosity function, LF), $\varphi(L)$, and the second is the normalized (over $z$) volume distribution of GRB events, $dR(z)/dz$.

The spatial distribution is defined by the differential rate equation (see Coward, Burman & Blair 2001; Coward 2007):

$$dR(z)/dz = 4\pi \left( c^3 r_0 / H_0^2 \right) e(z) F(z, \Omega_M, \Omega_\Lambda) / (1 + z),$$

where $dR/dz$ is the GRB differential event rate in units of $s^{-1}$ per unit redshift, $e(z)$ is the dimensionless source rate density evolution function [scaled so that $e(0) = 1$], $r_0$ is the GRB local rate density and $F(z, \Omega_M, \Omega_\Lambda)$ is a dimensionless cosmology-dependent function (equation 13.61 of Peebles 1993). A flat cosmology is assumed with $H_0 = 71\, \text{km\,s}^{-1}\,\text{Mpc}^{-1}$, $\Omega_M = 0.7$ and $\Omega_\Lambda = 0.3$. We assume that GRBs follow the star formation rate and take $e(z)$ to follow the SFR model of Hopkins & Beacom (2006). The differential volume factor is the dominant factor in this expression.

For $\varphi(L)$, we used equation (1) of Jóhannesson, Björnsson & Gudmundsson (2007).

$$\varphi(L) = C \left( \frac{L}{L_0} \right)^{-\lambda} \exp \left[ -\frac{\ln^2(L/L_0)}{2\sigma^2} \right] \exp \left( -\frac{L}{L_0} \right),$$

where $C$ is a normalization constant, $L_0$ a characteristic luminosity and $\lambda$ and $\sigma$ are parameters that control the shape of the function. Values for $\sigma$ and $\lambda$ were selected to match the R-band light curve from Jóhannesson et al. (2007) (see their fig. 1). This LF was converted into a pdf by normalizing it over the luminosity range for OAs [which, in absolute magnitude terms, we took as $[-25, -19]$] from fig. 3 of Kann et al. (2008) or fig. 5 of Kann et al. (2007)].

$L_0$ defines the upper exponential cut-off in the function and is set by the luminosity corresponding to an absolute magnitude of $-25$ (using, e.g. equation 2 of Salpeter & Hoffman 1986).

We also include in our simulations a redshift dependent LF: Two models are employed as follows.

(i) A continuously brightening luminosity distribution with $z$ (upper panel of Fig. 2, where the brightening is from $z = z_{\text{evolv}} = 1.5$ onwards).

(ii) A discontinuous change (lower panel of Fig. 2, where the brightening is from $z = z_{\text{evolv}} = 4$ onwards).

In both cases, modification of the LF merely involved shifting this distribution to higher brightness as $z$ increases without altering the shape of the LF itself.

To construct a synthetic population of afterglows an ensemble of GRB events is first generated in redshift space using equation (1). Afterglow luminosity values ($M_r$) are then generated according to the pdf of equation (2) and randomly assigned to one of the previously created events in redshift space, thus producing a synthetic

1 Telescope ‘response time’, $T_z$, is defined here as the time from the start of the prompt GRB to the measurement of a redshift from the OA.

2 LF refers to the luminosity function of the GRB OAs.

3 These magnitudes are standardized to one day after the burst. For the simulation, they were then scaled to the time of interest using the $t^{-\alpha}$ relationship (see equation 3).

4 But note the typographical error in the equation of this reference: ‘L’ is written in the denominator instead of ‘$L$’.

5 We use the term ‘evolving LF’ to mean a luminosity function whose base luminosity increases ‘fast enough’ with $z$ while preserving its functional shape. Note also that we are here using a brightening LF as a mathematical device. Physical interpretations are mentioned in Section 4.
population of OAs. The OA luminosities are all assumed to decay as \((T_z - t_0)^{-\alpha}\), with \(\alpha = 1\) and \(t_0\) the decay reference time (Kobayashi & Zhang 2007). With late-phase decay we can use the GRB response time, \(T_z\), to describe the decay by \(T_z^{-\alpha}\). (All times are measured in seconds in the observer’s rest frame.) At specific times after the burst \((T_z,i, i = 1, 2, 3, \ldots)\), we calculate the average redshift, \(\langle z_i \rangle\), for all the observable OAs. At these times, \(t_i (= T_z,i)\), after the start of the optical light-curve decay, the apparent magnitudes \(m(t_i)\) are calculated from the (temporally modified) Pogson’s formula:

\[
m(t_i) = M_c + 5 \log_{10}(d_L/10) + \frac{5\alpha}{2} \log_{10}(t_i/t_c) .
\]

The calibration absolute magnitude for the OA is defined by \(M_c \equiv M(t_c)\), and \(d_L\) is the luminosity distance in parsecs, calculated via the analytical form given by Pen (1999). The calibration time for all afterglows, \(t_c\), is 1 d, as per Kann et al. (2008) or Kann et al. (2007).

A telescope limiting magnitude \((m_l)\) is used to define a brightness threshold for obtaining a redshift. Any simulated apparent magnitude dimmer than this threshold is not observable and, hence, no redshift is measured. So, for each \(t_i\) all events for which \(m(t_i) \leq m_l\) are taken to be observable. For this simulation, we have taken \(m_l = 23\), so as to approximate a VLT-class instrument.

51 Monte Carlo runs, each with a population of 5000 OAs, were executed with each using different random number seeds to generate the OA populations. For each \(t_i\), the average redshift of all the observable OAs, \(\langle z_i \rangle\), was calculated over all runs. The results were found to be insensitive to the seeds used.

The simulation makes several simplifying assumptions while still retaining the gross features of the OA distribution and decay.

(i) We assume one limiting telescope magnitude, \(m_l\) – i.e. a single telescope class (and identical seeing conditions) is assumed for OA spectroscopic observations.

(ii) The temporal decay is modelled by a single power law with the decay index, \(\alpha\), taken to be the same for all OAs and all \(z\).

(iii) We ignore any \((\gamma\text{-ray})\) triggering thresholds and field-of-view limitations of a satellite detector.

4 RESULTS

Using the same LF for all \(z\) (i.e. a non-evolving LF), the simulated \(T_z - \langle z \rangle\) data consistently shows a negative correlation (i.e. the \(T_z - \langle z \rangle\) plot has a negative slope). This is expected from the Malmquist bias with a non-evolving LF, but it is opposite to the observational evidence reported by Coward (2009). By increasing the luminosity of the OA population with increasing redshift, it is possible for our model to reproduce the trend of the observed data. We note that an evolving LF in this model may result from any of the following reasons or a combination of them.

(i) An intrinsic brightening of the OA population with increasing \(z\) [e.g. fig. 2(c) of Badjin, Beskin & Greco (2009)].

(ii) Less local host extinction with increasing \(z\).

(iii) Increasing energy shifted into the optical band from higher frequencies with increasing redshift (K-correction).

The above will all manifest themselves as an increase in the overall brightness of the OAs, with or without the original source itself being intrinsically brighter. Hence, when modifying the OA LF in this simulation we understand that it may be due to a change in intrinsic

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Luminosity–redshift plots [Spaenhauer (1978) diagrams] for two example evolving OA LFs at calibration time, \(t_c\). The upper panel trials a continuously brightening population starting from \(z = 1.5\). The lower panel trials a discontinuous change, with brightening starting at \(z = 4\). Each trial function above results in a growing \(\langle z \rangle\) with \(T_z\). The purpose of using two different luminosity evolutions is merely to demonstrate qualitatively that enough brightness at high \(z\) will result in \(\langle z \rangle\) increasing with telescope response time, as exemplified by the simulation results in Fig. 3.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** The \(z\)-averaged results of all simulation runs showing the correlation of mean redshift with telescope response times to acquire a spectroscopic redshift. The LF evolution used in the simulation is that of the upper panel of Fig. 2. The trend towards higher \(\langle z \rangle\) with increasing \(T_z\) is the result of an OA population brightening with \(z\), for \(z > z_{\text{evolv}}\). A similar result occurs for the two-component LF shown in the lower panel of Fig. 2. Redshifts and response times obtained from the simulations are representative only, as they depend on various parameter values (e.g. telescope limiting magnitude \(m_l\), luminosity decay index \(\alpha\) and the distribution of these parameters. Our model is an idealization, which uses only a single value for each parameter.

Additionally, one of the most influential factors affecting results is the function describing LF evolution – something which is unknown at present.
source brightness, local extinction or frequency downshifting – or a combination of these. So, with this understanding, whenever we speak of ‘brightening OAs’ or ‘evolving LF’ we mean an increase in the overall brightness of the OA at redshift \( z \), whatever the cause.

Brightening the OAs with \( z \) (via, e.g. either of the two trial luminosity distributions shown in Fig. 2) yields a positive slope, similar to the observed data (compare Figs 1 and 3). With a monotonically brightening⁶ LF with redshift (upper panel of Fig. 2), the simulated \( T_{\gamma}(z) \) data yields a similar positive trend to the observations (compare Figs 1 and 3). Similar results hold if we use a two-component model, such as that displayed in the lower panel of Fig. 2.

The primary factor in achieving the result we seek is an increase in the relative luminosity of OAs with redshift.

If we are given the form of an evolving LF then the redshift where the LF starts evolving, \( z_{\text{evolv}} \), can be approximated. For a linearly brightening OA (upper panel of Fig. 2), setting \( z_{\text{evolv}} \) too high (from equation 1, the GRB event rate peaks at \( z \approx 2 \)) will result in too few OAs in the more distant Universe (\( z > z_{\text{evolv}} \)) with the consequence that the \( T_{\gamma}(z) \) relation weakens and tends to a negative correlation. There is also a trade-off between the rate of brightening and \( z_{\text{evolv}} \): the faster the rate of brightening with \( z \), the smaller \( z_{\text{evolv}} \) can be while still producing a positive correlation for \( T_{\gamma}(z) \).

It is instructive to note that the direction of variation of \( z \) differs depending on whether or not we are dealing with an evolving or non-evolving LF. The effect on \( z \) of individually varying \( \alpha, m_1 \) and \( T_2 \) is summarized in Table 1.

In summary, we find that with a fast enough brightening of OA luminosity with \( z \), the average GRB redshift distribution of the observed afterglows increases with telescope response time, in accord with observations. If a non-evolving LF is employed the \( T_{\gamma}(z) \) relation obtained from our simulation is in contradiction to the data. This result is insensitive to the shape of the LF but is dependent upon the function defining the evolution of the LF with \( z \).

### 5 DISCUSSION

As a result of brightening the GRB OA LF with \( z \), the proportion of bright OAs will increase with \( z \). Thus, if the LF brightens fast enough with \( z \) it can more than compensate for the decreasing number of OAs after \( z \approx 2 \) and the dimming effect of distance. In particular, for a long response time, the very bright and distant OAs increase the \( z \) as they start their decay from a much higher luminosity than closer and relatively dimmer OAs. Hence, because dimmer OAs fade out quicker as \( T_\gamma \) increases, the high-\( z \) OAs are observable for longer despite being more distant. This results in an increasing \( z \) as the response time increases.

Increasing the number of OAs at high \( z \) (Daigne, Rossi & Mochkovitch 2006) with an unevolving LF did not produce a positive correlation in \( T_{\gamma}(z) \) in our simulation and neither did modifying the shape of the LF. In fact, we found that the \( T_{\gamma}(z) \) result was insensitive to the shape of the OA LF but determined by the rate of the LF evolution.

Other parameters affect the results in a mostly quantitative manner: the more sensitive the telescope the stronger the \( T_{\gamma}(z) \) correlation becomes. Conversely, a larger \( \alpha \) results in a weaker correlation.

Within the limitations of our model, we find evidence that the observed time-dependent selection effect may be the result of an evolving LF (smooth or not) for OAs, with the relatively brighter afterglows occurring in the early Universe. The weak positive correlation between OA luminosity and \( E_{\gamma, \text{iso}} \) reported by Kann et al. (2007) and suggested by fig. 2(a) of Liang & Zhang (2006) raises the possibility that GRBs may have been evolving through time, with GRBs being more energetic in the early Universe.

Our use of an evolving LF in simulations is consistent with work that finds GRB bursts to be distributed between near low-luminosity and more distant and luminous GRBs (e.g. Cobb et al. 2006; Chapman et al. 2007; Liang et al. 2007). Nardini, Ghisellini & Ghirlanda (2008), Kann et al. (2007), Liang & Zhang (2006) and the left-hand panel of fig. 7 of Melandri et al. (2008)⁷ suggest that OA luminosities themselves may be partitioned into two or three populations.

In summary, we find that the trend of \( T_{\gamma}(z) \) is independent of the LF but governed by the strength of the LF evolution and the redshift regime where this evolution takes place.

On a more abstract level, we note that attempts are often made to eliminate or work around selection effects. However, in this study, we have found that a time-dependent selection effect has been helpful in extracting new insight into the GRB OA distribution. Perhaps in other studies, selection effects may also provide more illumination than obscuration.

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⁶ The choice of a linearly brightening absolute magnitude with \( z \) is taken purely on the grounds of simplicity as there is currently no evidence to favour any particular function.

⁷ Although these authors argue that their OA data do not support bimodality, the lack of nearby luminous bursts in their fig. 7 tends to support it.
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