Observations of GRBs at high redshift

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The extreme luminosity of gamma-ray bursts and their afterglows means they are detectable, in principle, to very high redshifts. Although the redshift distribution of gamma-ray bursts (GRBs) is difficult to determine, due to incompleteness of present samples, we argue that for Swift-detected bursts, the median redshift is between 2.5 and 3, with a few per cent probably at \( z > 6 \). Thus, GRBs are potentially powerful probes of the era of reionization and the sources responsible for it. Moreover, it seems probable that they can provide constraints on the star-formation history of the Universe and may also help in the determination of the cosmological parameters.

Keywords: gamma-ray bursts; host galaxies; cosmic reionization

1. Introduction

Long-duration gamma-ray bursts (GRBs) are becoming powerful probes of the distant Universe. The overriding asset of GRBs is extreme luminosity over a very broad wavelength range, which in principle allows them to be seen and studied to very high redshift, \( z \sim 20 \) (Lamb & Reichart 2000). They can be detected in gamma rays even in the presence of high column densities of intervening material, removing one potential source of incompleteness bias. Furthermore, having stellar progenitors, they can be detected irrespective of the luminosity of the star-forming host itself. The drawback of GRBs is, of course, their rarity and, even in the Swift era, it continues to be a time-consuming business building up statistically useful samples.

The highest redshift found to date is \( z = 6.30 \) for GRB 050904 (Haislip et al. 2006; Kawai et al. 2006). This compares well to the most distant galaxy with a confirmed spectroscopic redshift of \( z = 6.95 \) (Iye et al. 2006). The number density of bright galaxies (and quasars) decreases rapidly at early times, as expected in hierarchical growth of structure, making them increasingly rare and hard to detect at \( z > 6 \) (cf. Reed et al. 2003), and hence making the searches for even higher redshift GRBs all the more important.

In this review, we first consider the crucial question of the redshift distribution of GRBs and what we can say about the numbers likely to be found at very high

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redshifts. This includes consideration of the importance of ‘dark bursts’: those with very faint or undetected optical afterglows.

We then outline some of the scientific programmes proposed or underway to use GRBs to illuminate a number of cosmological questions, particularly considering the role of GRBs as star-formation indicators, and as a means of studying high-redshift galaxies and their environments.

2. The redshift distribution of gamma-ray bursts

Various authors have attempted to predict the redshift distribution of GRBs. The ingredients of such models are basically (i) a parametrization or prediction of the star-formation history of the Universe, combined with (ii) some mapping from star-formation rate to GRB rate and luminosity, and finally (iii) convolving with a selection function dependent on the instrument used for initial detection. The star-formation history of the Universe is already uncertain, particularly beyond $z = 5$, which of course is one of the motivations for pursuing GRB studies, as discussed below. Mapping star-formation rate onto GRB rate, essentially an attempt to guess the sensitivity of GRB rate and/or luminosity on factors such as metallicity, and indeed the metallicity distribution among the stellar populations present at a given redshift, is currently a matter of educated guesswork. Even the selection function of Swift/burst alert telescope is non-trivial, since the detectability of a given GRB depends on its spectrum and photon time history, along with instrumental factors such as position in field of view and the state of the (evolving) detection algorithm.

Despite all these provisos, it is important to have some predictions for plausible rates. Notable recent attempts include the following: Guetta et al. (2005) explore a variety of different star-formation rate histories and GRB luminosity functions; Natarajan et al. (2005) additionally incorporate a simple prescription for a low-metallicity preference for GRBs; Yoon & Langer (2005) take a more sophisticated approach to the metallicity question by explicitly identifying stellar evolution models, which naturally lead to collapsar progenitors; and Bromm & Loeb (2006) further consider the possibility of a population III contribution to the high-$z$ GRB rate.

The observed redshift distribution should also be treated with caution because it is susceptible to further important selection effects. For example, those GRBs with bright optical afterglows are much more likely to have a redshift measured than those for which the optical afterglow is faint (cosmic time dilation does help here to some extent, since at fixed observer time we see an earlier, and usually intrinsically brighter phase of the afterglow).

In fact, of all the GRBs which have been reasonably well localized, less than 40% have had direct redshift measurements, making them a highly incomplete sample. A few redshifts have been measured for dark bursts, but only when the GRB is pinned down well enough by its X-ray or radio position to identify a probable host, and the host itself is sufficiently bright to obtain a spectroscopic redshift. However, it is important to remember that in many cases the lack of an optical afterglow may be blamed on poor positioning of the burst, for example, at low galactic latitude, or being too close to the Sun or bright Moon for deep follow-up.

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In an effort to improve this situation, Jakobsson et al. (2006) defined a subset of all GRBs well placed for optical observation. The selection criteria were that the burst should have an X-ray position made public within 12 h, the galactic foreground be low $A_V < 0.5$, the burst be greater than 55$^\circ$ from the Sun, and not at a polar declination, $|\text{dec}| < 70^\circ$. Imposing these restrictions reduces the GRB sample size, but greatly increases the redshift completeness of those samples. In fact, Jakobsson et al. (2006) were able to show that the median redshift of Swift discovered GRBs is considerably higher than that of pre-Swift GRBs. An updated illustration of this difference is shown by the labelled lines in figure 1.

Unfortunately, even with the above restrictions, only 50–60% of the Swift GRB sample have good redshifts (spectroscopic or photometric with many bands). However, many of the remaining bursts do at least have detections in UV, optical or nIR bands, which can be used to place an upper limit to their redshift. In particular, when detected in the UV by UV/optical telescope, the upper limits can be relatively low. Indeed, fewer than 20% of bursts in the sample have no constraint on their redshift.

To visualize the maximum possible effect of redshift incompleteness, we also plot in figure 1 a bold line which includes now all the bursts satisfying the selection criteria, but placing those with no firm redshift at the maximum redshift they can have, given their bluest photometric detection. Reality is likely...

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**Figure 1.** Cumulative histograms of redshifts obtained for uniformly selected samples of long-duration bursts as of end November 2006. The pre-Swift sample had a relatively low-median redshift around $z = 1$. For the Swift GRBs (selected following the criteria of Jakobsson et al. 2006), the two lines are (i) an incomplete subsample with only those 43 bursts with well-determined redshifts, and (ii) the full sample of 83, including 40 bursts without redshifts (i.e. generally optically fainter) placed in the distribution according to their upper redshift limits based on photometry. The true, optically unbiased Swift redshift distribution is likely, therefore, to be between these two lines.

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to lie somewhere between the rightmost curves, which is consistent with the Bromm & Loeb (2006) prediction that approximately 10% of Swift GRBs should lie beyond $z=5$.

3. Gamma-ray bursts as a means of studying high-$z$ galaxies

Most of the methods used to find and study high-redshift galaxies rely on detecting the galaxy in some waveband. In particular, in recent years, Lyman-break galaxies, identified via their optical (rest-frame UV) colours (Steidel et al. 2003), sub-millimetre galaxies (Ivison et al. 2005) and Lyman-$\alpha$ emission line galaxies (Iye et al. 2006; Malhotra & Rhoads 2006), have been central to our understanding of the high-$z$ galaxy population. However, since these techniques all rely on the galaxy being luminous enough to make it into the samples, they are biased towards the bright end of the galaxy LF in whichever waveband the search is performed.

Quasar absorption lines can be used to locate galaxies based on absorbing column rather than luminosity, but it can be problematic to identify the counterpart in emission against the bright quasar point source.

GRBs, on the other hand, have stellar progenitors and therefore select galaxies independent of their luminosities. Their afterglow absorption line spectra give redshifts, and indeed chemical and dynamical information about the host’s interstellar medium, even for extremely faint galaxies. Furthermore, once the afterglow has faded, the host can be studied directly. A good example of the power of GRBs as a means of selecting high-redshift galaxies is that of GRB 020124, which was undetected in a deep HST pointing to $R\approx 29.5$ (Berger et al. 2002), and yet was found to be a damped Lyman-$\alpha$ system at $z=3.20$ through the follow-up of its afterglow (Hjorth et al. 2003a). Vreeswijk et al. (2004) made a pioneering high-S/N observation of another notable burst with a faint host galaxy, that of GRB 030323 with $R_{AB}\approx 28$, showing it to have a metallicity only a few per cent of solar.

Studies of host samples continue to be troubled by the incompleteness of spectroscopy. However, despite that, interesting comparisons have been made between GRB hosts and other populations. In particular, Fruchter et al. (2006) recently compared GRB hosts with the hosts of core-collapse supernovae in the same redshift range, and showed them to have quite different morphologies and luminosities on the average. Since both are thought to have massive star progenitors, this is surprising, although it confirms the long-noted fact that many GRB hosts are rather small, irregular galaxies, and could be a consequence of a metallicity dependence of GRB properties.

4. Gamma-ray bursts as tracers of star formation

Since GRBs are produced by massive stars (e.g. Hjorth et al. 2003b), which have short lifetimes, one would expect the rate of GRBs is proportional to the massive star-formation rate at any given epoch (e.g. Wijers et al. 1998). Assuming a universal IMF (in common with most other SFR estimation techniques) allows us to infer a total star-formation rate history.
Advantages of GRBs as star-formation indicators are that they are very bright and can be seen through high columns of gas and dust. Furthermore, as discussed above, we can count GRBs as a function of redshift even when their hosts are too faint to have appeared in any photometric census of star formation.

Our hope then is that if GRBs can be shown to be an unbiased tracer of star formation, then the redshift distribution of GRBs can, in principle, be inverted to give the global star-formation rate history. The proportion of star formation occurring in different populations of galaxies should be reflected in the proportions of such galaxies among the GRB hosts.

This hypothesis can be tested by looking at the distribution of star-forming properties of GRB hosts. In the optical/UV, Jakobsson et al. (2005) found that a small sample of GRB hosts with $z \geq 2$ had a luminosity function consistent with being a star-formation-weighted Lyman-break galaxy luminosity function. Since a large proportion of high redshift star formation is thought to be dust-obscured, it is of particular interest to investigate the fIR/sub-millimetre/radio properties of GRB hosts. Early results showed that some hosts were indeed detectable in sub-millimetre or radio (Frail et al. 2002; Barnard et al. 2003; Berger et al. 2003b). Included among the target sample were a number of hosts of dark bursts (identified via accurate X-ray locations), helping mitigate against an optical bias.

However, subsequently it has become clear that the numbers are significantly below predictions based on the expected high proportion of global star formation taking place in ultra-luminous dusty galaxies (e.g. Tanvir et al. 2004; Le Floc’h et al. 2006; Priddey et al. 2006). The conclusion of these studies is that while GRB hosts are in general actively star forming, very few are intensively star-forming ULIRG-like galaxies. Once again, a plausible explanation is that GRBs are selecting smaller, lower metallicity galaxies (cf. Fynbo et al. 2003), which would make them less useful as a probe of all star formation, but possibly increasingly useful as a tracer of higher redshift star formation.

5. Gamma-ray bursts as a means of studying the era of reionization

In conventional cosmology, after recombination, the Universe remained neutral until the first collapsed sources began to emit UV radiation. This radiation ionized a region around each source, and these regions eventually grew and merged to form a nearly fully ionized intergalactic medium by a redshift of approximately $z=6$. This is known from spectroscopy of high-redshift quasars, which show that the neutral fraction was low (and dropping) at these redshifts.

Measurements of the electron-scattering optical depth by the Wilkinson Microwave Anisotropy Probe observations of the microwave background, however, indicate that reionization was substantially underway at earlier times, around $z=11$ (Page et al. submitted; Spergel et al. submitted). The epoch of the very earliest collapsed sources and the detailed time history of reionization, which may have proceeded in a slow continuous way or in separate population III and population II phases, remain open questions (e.g. Furlanetto & Loeb 2005).

There is considerable interest in the nature of the first objects and the phase change that they brought about. However, probing further with QSOs becomes difficult owing to the rapidly diminishing number density of bright QSOs beyond...
QSO spectra are also difficult to analyse due to the bright emission lines and the substantial ‘proximity’ effect that a bright QSO has on the surrounding intergalactic space. GRBs, on the other hand, have stellar progenitors, and so may well be frequent in the high-z universe. They tend to reside in small galaxies, with little proximity effect, and they have power-law continua against which it is relatively easy, in principle, to measure absorption features (e.g. Mesinger et al. 2004).

The difficulty with GRBs is, of course, their transience and rarity. It is therefore essential that any high-z bursts that are discovered are identified as such as soon as possible, and followed up with nIR spectroscopy while the afterglow is still bright. In the case of GRB 050904, the afterglow was already very faint when the Subaru spectrum was obtained, but an estimate of the neutral fraction was still possible (Kawai et al. 2006; Totani et al. 2006).

6. Gamma-ray bursts to measure cosmological parameters

Given the diverse behaviour of GRBs, particularly of their prompt emission, the prospects for their use as distance indicators would not seem promising at first sight. Nonetheless, Berger et al. (2003a) showed that after correcting for beaming the majority of bursts seemed to have a ‘standard reservoir’ of energy that they released. Several other authors have also explored the correlation between GRB luminosity (or energy) and other parameters that are independent (or partially independent) of distance. Notably, Ghirlanda et al. (2004) found a remarkably tight relation collimation-corrected energy and the peak energy of the $vF_v$ prompt spectrum.

The advantage of GRBs in this area is that they are found to be considerably higher redshifts than SNeIa, and so provide a complementary constraint on
cosmological world models. The main drawback at present is that there is only a small and rather inhomogeneous sample of bursts available, which must be used to both calibrate the relation and provide cosmological constraints. For further discussion, see Ghirlanda (2007).

7. Conclusions

We have seen that long-duration GRBs hold considerable promise as probes of the high-redshift universe. As a final illustration, in figure 2 we show the history of the most distant-known quasar, galaxy and GRB over the past 50 years. Although only a relative newcomer to this game, GRBs have rapidly become competitive, and there are reasons to hope that with Swift, GLAST and other satellites providing hundreds of localizations over the next few years, that they may become the method of choice for studies of the earliest era of structure formation.

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References


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