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 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 percent likely at $z > 6$. Thus, GRBs are potentially powerful probes of the era of reionization, and the sources responsible for it. Moreover, it seems likely 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 with 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 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 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 under way 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 GRBs

Various authors have attempted to predict the redshift distribution of GRBs. The ingredients of such models are basically (a) a parametrization or prediction of the star-formation history of the universe; combined with (b) some mapping from star-formation rate to GRB rate and luminosity; and finally (c) 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 amongst the stellar populations present at a given redshift, is currently a matter of educated guess-work. Even the selection function of *Swift*/BAT 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: Guetta, Piran & Waxman (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; 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-localised, 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 likely host, and the host itself is a 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 followup.

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 hours, the Galactic foreground be low $A_V < 0.5$, the burst be $> 55°$ from the Sun, and not at a polar declination, $|\mathrm{dec}| < 70°$. 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 red and blue lines in figure 1.

Unfortunately, even with the above restrictions, only 50–60% of the *Swift* GRB

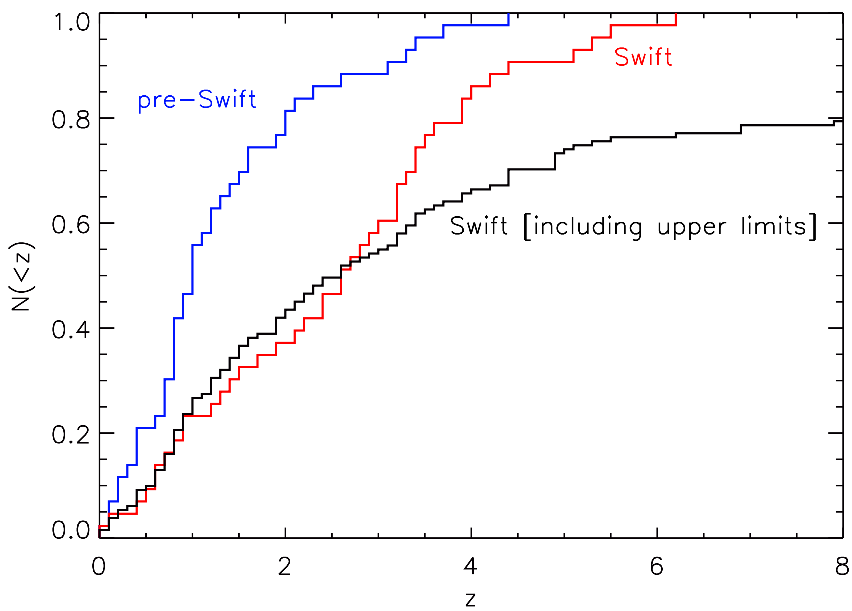

Figure 1. Cumulative histograms of redshifts obtained for uniformly-selected samples of long-duration bursts as of end November 2006. The pre-*Swift* sample (blue) had a relatively low median redshift around $z = 1$. For the *Swift* GRBs (selected following the criteria of Jakobsson *et al.* 2006) the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

sample have good redshifts (spectroscopic or photometric with many bands). However, many of the remaining bursts did 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 UVOT, the upper limits can be relatively low. Indeed less than 20% of the sample have no constraint on their redshift.

To visualise the maximum possible effect of redshift incompleteness we also plot in figure 1 a black 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 to lie somewhere between the red and black curves, which is consistent with the Bromm & Loeb (2006) prediction that $\sim$10% of *Swift* GRBs should lie beyond $z = 5$.

3. GRBs 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 (LBGs), identified via their optical (rest-frame UV) colours (Steidel *et al.* 2003); submm galaxies (Ivison *et al.* 2005); and Lyman-α emission line galaxies (Malhotra & Rhoads 2006; Iye *et al.* 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 independently 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-α system at $z = 3.20$ through followup 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 percent 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 to 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. GRBs as Tracers of Star Formation

Since GRBs are produced by massive stars (eg. Hjorth *et al.* 2003b), which have short life-times, one would expect the rate of GRBs is proportional to the massive star formation rate at any given epoch (eg. 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 unbiassed 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 occuring in different populations of galaxies, should be reflected in the proportions of such galaxies amongst 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 $z \gtrsim 2$ 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/submm/radio properties of GRB hosts. Early results showed that some hosts were indeed detectable in submm or radio (Frail *et al.* 2002; Barnard *et al.* 2003; Berger *et al.* 2003b). Included amongst 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 (eg. Tanvir *et al.* 2004; Priddey *et al.* 2006; Le Floc'h *et al.* 2006). The conclusion of these studies is that whilst 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. GRBs 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 about $z = 6$. 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 Microwave Anisotropy Probe (WMAP) observations of the microwave background, however, indicate that reionization was substantially under way at earlier times, around $z = 11$ (Page *et al.* 2006; Spergel *et al.* 2006). 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 pop III and pop II phases, remain open questions (eg. 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 because of the rapidly diminishing number density of bright QSOs beyond $z = 6$. 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 (eg. Mesinger, Haiman & Cen 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 (Totani *et al.* 2006; and Kawai *et al.* 2006).

6. GRBs 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 promissing at first sight. Nonetheless Berger, Kulkarni & Frail (2003) 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, Ghisellini & Lazzati (2004) found a remarkably tight relation collimation-corrected energy and the peak energy of the νF_ν prompt spectrum.

The advantage of GRBs in this area is that they are found to considerably higher redshifts than SNeIa, and so provide a complementary constraint on cosmological world-models. The main drawback at the 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 in this volume.

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 new-comer to this game, GRBs have rapidly become competetive, and there are reasons to hope that with *Swift, GLAST* and other satellites providing hundreds of localisations 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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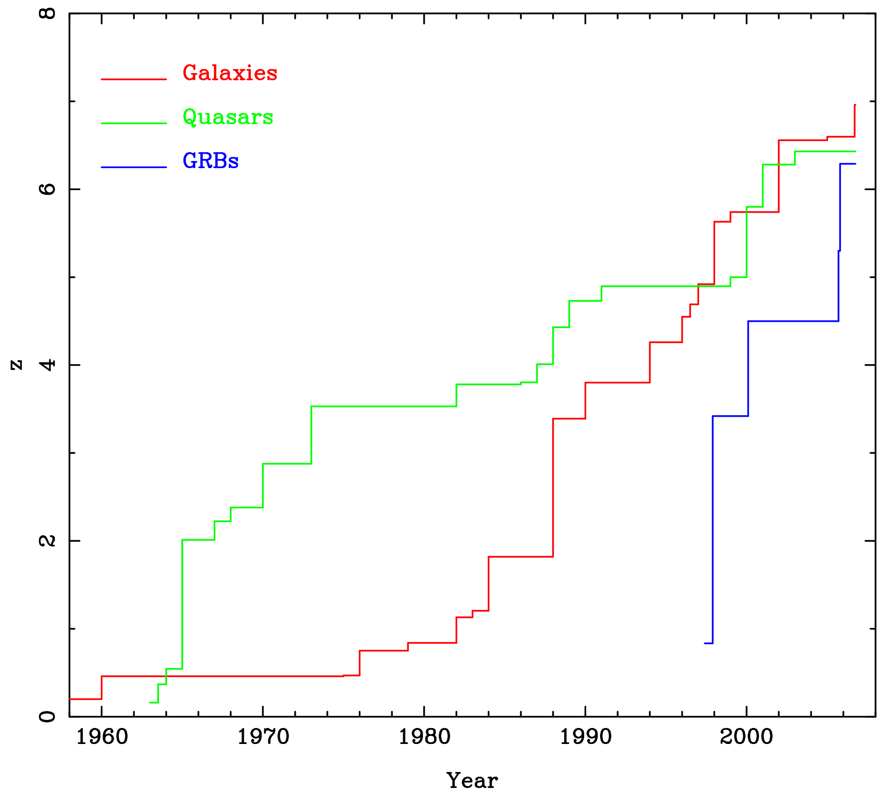

Figure 2. A representation of the historical increase in the highest known redshift for quasars and galaxies as compared to GRBs.

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