The highest redshift gamma-ray bursts

NIAL TANVIR

Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH, United Kingdom

I review the searches for gamma-ray bursts at very high redshift. Although the numbers of GRBs known at $z > 6$ remain few, even small samples can provide information about early star and galaxy formation in the universe which is very hard to obtain by any other means.

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1 Introduction

The formation of early collapsed structures in the universe, and the processes of enrichment and reionization that they initiated, are topics of intense current interest. Detection of individual galaxies at $z > 7$ has proven highly challenging and, although moderately large samples of candidates have been identified using a combination of Hubble Space Telescope and Spitzer Space Telescope photometry \cite{1}, it still appears likely that they include low-$z$ interlopers \cite{2}. In addition, the evidence suggests that the dominant proportion of star formation at these times was taking place in galaxies below the HST detection limit \cite{3}, limiting the conclusions that can be drawn.

It has long been argued that long-duration gamma-ray bursts (GRBs), thanks to their extreme luminosities and association with massive star death (and hence star formation) are potentially powerful probes of the early universe, providing access to information that is hard to obtain in other ways (e.g., \cite{4,5}).

2 Discovery of high redshift GRBs

High redshift ($z > 6$) GRBs have generally been identified first as candidates via optical and infrared (nIR) photometry of their afterglows, where they stand out as dropout sources in bluer bands, ideally together with a blue continuum slope in the redder bands \cite{6}. Spectroscopic detection of the Lyman-α break provides a clear feature from which definitive redshifts are obtained. In this way, several GRBs have now been confirmed at $z > 6$ \cite{7,8,9,10}.

There have also been instances where no spectrum was obtained, due to poor weather conditions and/or limited availability of nIR spectrographs. In these cases, photometric redshifts can provide strong constraints, albeit with larger uncertainties. The most notable example is that of GRB 090429B with a photo-$z \approx 9.4$, although with some dust contribution to the reddening, this could have been as low as $z \sim 7$ \cite{11}. In this regard, GRB afterglows have the advantage over galaxies of having simple power-law spectra, and so photometric redshifts are generally more robust and not subject to catastrophic errors \cite{12}.

A recent very high redshift burst is GRB 120923A. Work on the spectra of that event is ongoing, but a provisional analysis of the photometric data indicates $z \approx 8.5$, as shown in Figure \cite{1}.

3 The potential of spectroscopy

Afterglow spectra can also provide key diagnostics of the environments of the bursts. Only the red wing of the Lyman-α line is typically seen at high redshift, due to the continuum to the blue being absorbed by neutral hydrogen in the intergalactic
Figure 1: Spectral energy distribution of the afterglow of GRB 120923A, showing it to be best fit (red line) by a power-law cut off by a Lyman-α break at $z \approx 8.5$. Note, photometric data have been extrapolated to a common time using the measured broken power-law light curve.

medium (IGM). However, with a sufficiently high signal-to-noise spectrum, and a redshift precisely determined via metal absorption lines, the red wing can be fitted simultaneously by an IGM component along with a component due to the interstellar medium in the host galaxy. Both of these components potentially provide key diagnostics. The former gives the IGM neutral fraction proximate to the host, and thus a measure of the progress of reionization; if this can be achieved for a sample of GRBs at different redshifts, then the time history and sight-line to sight-line variance of reionization can be constrained [13]. The latter, the HI column due to the host, can be used to infer the opacity of the gas to ionising radiation, and hence the escape fraction. Once again, if this can be achieved for a substantial sample of GRBs, then the distribution of escape fractions to high-$z$ star-formation would be deduced [14].

This is important since a high escape fraction is required in order for stars to provide the necessary photon budget to drive reionization. We note that the host HI absorption is also required in order to translate the column densities of metal lines into abundances relative to hydrogen, but once achieved, this can provide unique insights into chemical enrichment in star forming galaxies at $z > 2$, e.g. [15].

So far there has been rather limited success in pursuing this goal at $z > 6$, due to the low rate of high redshift GRBs in general, and of intrinsically bright afterglows in particular. However, an early success with GRB 050904 at $z = 6.3$, pointed to the potential of this approach [16], and GRB 130606A looks likely to provide a further opportunity to apply these techniques. In the long run, spectroscopy of even faint
high-z GRB afterglows with 30 m class telescopes should enable exquisitely precise measurements to be obtained.

4 The population of high redshift GRBs

It is interesting to ask how the GRBs found at high redshift compare to the lower redshift population. Of course, bright bursts with bright afterglows are more likely to be localised by Swift and have their redshifts measured via optical/nIR spectroscopy. The selection of bright bursts is illustrated in Figure 2, which shows the intrinsic peak luminosity ($k$-corrected to a common energy band of 30–300 keV using the observed spectrum) versus redshift for the sample of Swift GRBs with redshifts.

In order to precisely localise and obtain a redshift it is also required that the bursts have intrinsically bright afterglows in the observed nIR. Figure 3 shows that the five highest redshift bursts in fact span a fairly large range in brightness compared to a sample of optically observed afterglows at lower redshift (although this comparison sample itself is biased against including particularly faint afterglows). This suggests that the selection effect due to limitations of ground observations is not the overriding consideration, although doubtless some bursts detected by Swift are missed due to insufficient opportunity for ground follow-up.

Generally, the high-z GRB sample seems to be drawn from the same population as observed at lower-z, although see Littlejohns et al. (this conference) for indications that the rest-frame durations of $z > 5$ GRBs may be on average shorter.

5 The host population

To date, there have been no detections of $z > 6$ GRB hosts in deep imaging, which is consistent with the bulk of star formation in the reionization era occurring in faint galaxies, below the effective detection limit of HST [18]. It will clearly be of considerable interest to target the sample of $z > 6$ GRB hosts with JWST when it is launched.

6 Conclusions

The sample of $z > 6$ GRBs continues to grow, and are beginning to provide interesting results impacting on early star formation and galaxy evolution. Overall, numbers remain small, though, and while difficulties of followup likely mean that some proportion of Swift detected high-z events are being missed, the rest-frame properties of the observed sample suggest that even faint and difficult afterglows are being found. All this motivates new missions dedicated to locating high-z GRBs.
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Figure 2: Plot of peak luminosity versus redshift, for all Swift bursts where a redshift has been measured. Several of the highest redshift bursts have been labelled, and those in the TOUGH sample [17] (which has a high degree of redshift completeness, and therefore small optical bias) shown as bold symbols. The lower envelope is imposed by the BAT detection threshold, although we note that in practice there are a large number of trigger algorithms used, and so the selection limit is not simply a function of peak luminosity.
Figure 3: The rest-frame optical light curves of a large number of GRBs, artificially redshifts to show how they would appear at $z = 8.5$ (grey lines are broken power-law model fits to data from [19]), together with individual data points [6, 8, 9, 11] for several of the known highest redshift GRBs (also shifted to $z = 8.5$).