Gamma-ray bursts and cosmology

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I review the current status of the use of gamma-ray bursts (GRBs) as probes of the early Universe and cosmology. I describe the promise of long GRBs as probes of the high redshift \( z > 4 \) and very high redshift \( z > 5 \) Universe, and several key scientific results that have come from observations made possible by accurate, rapid localizations of these bursts by Swift. I then estimate the fraction of long GRBs that lie at very high redshifts and discuss ways in which it may be possible to rapidly identify—and therefore study—a larger number of these bursts. Finally, I discuss the ways in which both long and short GRBs can be made ‘standard candles’ and used to constrain the properties of dark energy.

Keywords: gamma-ray bursts; cosmology; dark energy; reionization; X-rays

1. Introduction

Gamma-ray bursts (GRBs) are far and away from the brightest events in the Universe, with gamma-ray luminosities that are frequently 10 billion times greater than the optical luminosities of the supernovae, with which they are associated, or of their host galaxies. It is no surprise then that the bursts should be easily detectable out to redshifts \( z \approx 20 \) (Lamb & Reichart 2000).

What is somewhat surprising is the fact that the IR and near-IR afterglows of long GRBs are also expected to be detectable out to very high redshifts (Lamb & Reichart 2000). The reason is that while the increase in distance and the redshift of the spectrum tends to reduce the spectral flux in a given frequency band, cosmological time dilation tends to increase it at a fixed time of observation after the GRB, since afterglow intensities decrease with time. These effects combine to produce little or no decrease—and can even produce an increase—in the spectral energy flux of GRB afterglows beyond \( z \geq 3 \) (Chiardi & Loeb 2000; Lamb & Reichart 2000). Consequently, GRBs can be used as powerful probes of the very high redshift Universe (Lamb & Reichart 2000).

Long GRBs can be made ‘relative standard candles’, using a relation that has been found between the peak energy \( E_{\text{peak}} \) of the spectrum in \( \nu F_\nu \), their isotropic equivalent energy \( E_{\text{iso}} \) in the rest frame of the burst source and the time of the so-called jet break seen in the optical afterglows of many bursts (Ghirlanda et al. 2004b; Liang & Zhang 2005; Nava et al. 2006). This can also be done using a second relation that has recently been found between the peak energy \( E_{\text{peak}} \), the peak luminosity \( I_{\text{iso}} \) and \( T_{0.45} \), a measure of the duration of the burst

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If detected by gravitational wave detectors, short GRBs can be made into ‘absolute standard candles’ (Dalal et al. 2006). Thus, both long GRBs (Ghirlanda et al. 2004a; Dai et al. 2004, Ghirlanda et al. 2006; Firmani et al. 2006b) and short GRBs (Dalal et al. 2006) can be used to constrain the properties of dark energy.

2. GRBs as probes of the very high redshift Universe

Figure 1 places GRBs in a cosmological context (Lamb 2002). At recombination, which occurs at redshift $z \approx 1100$, the Universe becomes transparent. The cosmic background radiation originates at this redshift. Shortly afterwards, the temperature of the cosmic background radiation falls below 3000 K and the Universe enters the ‘dark ages’ during which there is no visible light in the Universe. ‘First light’, which occurs at $z \approx 20$, corresponds to the epoch when the first stars form. Ultraviolet radiation from these first stars reionizes the Universe. Afterwards, the Universe is transparent in the ultraviolet.

Important cosmological questions that observations of long GRBs and their afterglows may address include the following (Lamb & Reichart 2000).

— The moment of first light and the earliest generations of stars merely by the detection of GRBs at very high redshifts.
— The star-formation history of the Universe, particularly that of massive stars, from the rate of GRBs as a function of redshift.
— The heavy element history of the Universe—in the star-forming regions of the galaxies in which the bursts occur, and in the damped Lyman $\alpha$ (DLA) and Lyman $\alpha$ forest clouds along the line of sight from the bursts to us—by observing metal absorption line systems in the spectra of GRB afterglows.
— The reionization history of the Universe by observing the shape of the red damping wing of the Gunn–Peterson trough due to Lyman $\alpha$ and Lyman $\beta$ absorptions in the spectra of GRB afterglows.
3. Recent scientific results

Figure 2 shows that Swift BAT is localizing many more high redshift ($z>4$) GRBs than earlier missions, and has localized the very first GRBs at very high redshifts ($z>5$). These bursts are providing new ways to probe the high redshift Universe. Here we describe two of them.

(a) Heavy element history of Universe

Figure 3a,b shows the relative abundances of iron to zinc and silicon to zinc, respectively, as a function of ZnII column density (Savaglio in press). This figure shows that GRB-DLAs (filled circles) and quasar (QSO)-DLAs (open squares) occupy two distinct regions, suggesting different physical properties for the two populations. In particular, GRBs appear to probe sites with much higher column densities. The correlations in the relative abundances and the ZnII column density seen in both panels provide clear evidence that dust depletion increases with increasing column density.

Figure 4 shows the evolution of the metallicity relative to solar values with redshift for GRB-DLAs (filled circles) and QSO-DLAs (open squares; Savaglio in press). This figure shows that the metallicity of both GRB-DLAs and QSO-DLAs increases with the age of the Universe, as expected. The metallicity of the GRB-DLAs is on average approximately five times larger than that of the QSO-DLAs. This is most probably because GRBs probe the star-forming regions in the discs of galaxies, whereas QSOs probe DLA clouds that have undergone less star formation.

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Reionization history of the Universe

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Figure 3. (a) Relative abundances of iron to zinc and (b) silicon to zinc as a function of ZnII column density for GRB-DLAs (filled circles) and QSO-DLAs (open squares). Also shown are the measurements for the ISM of the Milky Way and Magellanic Clouds (open circles). The dashed curves in (a) are model predictions for visual extinction values from left to right of $A_v = 0.005, 0.05, 0.5$ and 5. From Savaglio (2006).

Figure 4. Evolution of the metallicity relative to solar values with redshift for nine GRB-DLAs (filled circles) and 197 QSO-DLAs (open squares). The solid and dashed lines indicate the best-fit linear correlations for GRB-DLAs and QSO-DLAs. The GRB-DLAs metallicity is on average approximately five times larger than that in QSO-DLAs. The age of the Universe (Hubble time) is indicated along the top axis. From Savaglio (2006).

(b) Reionization history of the Universe

The reionization history of the Universe is critical to understanding the formation of stars (and therefore galaxies), since stars are unlikely to form in

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regions where hydrogen has been reionized. GRBs have the following numerous advantages as probes of reionization (Lamb & Haiman 2003):

— GRBs are by far the most luminous events in the Universe and are therefore easy to find and observe (much easier than QSOs and Ly α emission line galaxies),
— GRBs occur at much higher redshifts than QSOs,
— the NIR/IR afterglows of GRBs are easily detectable out to VHRs,
— GRBs and their afterglows produce no ‘proximity effects’ (i.e. no dynamical disturbance or ionization of the nearby IGM), and
— GRB afterglows have simple power-law spectra and dramatically outshine their host galaxies, making it relatively easy to determine the shape of the red edge of the Gunn–Peterson trough due to Ly α and Ly β absorptions.

Figure 5 shows the spectrum of the afterglow of GRB 050904 (Cusumano et al. 2006), the first VHR GRB discovered (Haislip et al. 2006; Tagliaferri et al. 2006), taken 3.5 days after the burst (Kawai et al. 2006). Clearly evident in the spectrum are the strong metal absorption lines from the host galaxy, and absorption due to both Ly α and Ly β. Deriving the shape—and therefore the ionization state and the clumpiness of the IGM—is, in principle, straightforward owing to the simple power-law shape of the afterglow spectrum. Because the cross-section for Ly β absorption is much smaller than that for Ly α absorption, the red damping wing due to Ly β absorption can be used to probe the reionization history of the Universe to higher redshifts. In the particular case of GRB 050904, the column density due to neutral hydrogen in the host galaxy exceeded that due to the IGM, so information could be gleaned only about the
former (Kawai et al. 2006; Totani et al. 2006). However, the opposite is expected to be the case for approximately half of all GRBs, according to statistics recently compiled by H.-S. Chen (2006, private communication).

4. Identifying VHR GRBs

Figure 6 shows the locations of the six GRBs having redshifts $z>4$ that have been detected so far, overlaid on the distribution of all Swift GRBs, in the ($F_N$, $S_N$)-plane. Here, $F_N$ and $S_N$ are the peak photon number flux and the photon number fluence, respectively, in the 15–150 keV energy band. Also shown are the trajectories of three of these GRBs in this plane as a function of redshift, using their burst-average spectra.

Figure 6. Ability of Swift to detect VHR GRBs. Shown are the locations of the six GRBs having redshifts $z>4$ that have been detected so far, overlaid on the distribution of all Swift GRBs, in the ($F_N$, $S_N$)-plane. Here, $F_N$ and $S_N$ are the peak photon number flux and the photon number fluence, respectively, in the 15–150 keV energy band. Also shown are the trajectories of three of these GRBs in this plane as a function of redshift, using their burst-average spectra.

$F_N$ (15–150 keV) [ph cm$^{-2}$ s$^{-1}$] $S_N$ (15–150 keV) [ph cm$^{-2}$]

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Prior to the launch of Swift, theorists had estimated that 10–25% of the bursts localized by Swift GRBs would lie at VHRs (Lamb & Reichart 2000; Bromm & Loeb 2002; 2006). What can we now say about this percentage on the basis of the GRBs detected by Swift during its first year-and-a-half of full operation? Of the 139 long GRBs localized as of this writing, afterglows have been detected in the optical and/or NIR for 68 GRBs (i.e. 50%) and redshifts have been determined for 35 GRBs (i.e. 26%). Of the latter, four lie at VHRs. A rather uninformative upper bound on the percentage of Swift long GRBs that lie at VHRs can be obtained by assuming that all of the bursts for which no optical afterglow was detected lie at VHR, plus the four bursts with measured redshifts \( z > 5 \). This gives an upper limit of 58%. Using a subset of Swift bursts that were well positioned for the follow-up studies, and again assuming that all of the bursts for which no optical afterglow was detected lie at VHR, Tanvir & Jakobsson (2007) derive a more informative upper limit of 22%.

Detecting the afterglows and determining the redshifts of VHR bursts (i.e. bursts that are undetectable in the optical) are more difficult than for bursts at lower redshifts. Thus, a lower bound on the fraction of Swift bursts that lie at VHRs is just the number (4) of long GRBs with measured redshifts \( z > 5 \) divided by the total number of long GRBs with measured redshifts (35). This gives a lower bound of 12%.

Thus, on the basis of the GRBs detected by Swift during its first year-and-a-half of full operation, we estimate that 12–22% of Swift GRBs lie at VHR. Despite this, spectra—which yield the real science pay-off from VHR GRBs—have been obtained in the optical for only a single VHR burst, and in the NIR for none.

5. VHR GRB spectroscopic pipeline

Why is this? The reasons are evident from figure 7, which shows the VHR GRB spectroscopic pipeline. Of the 139 long GRBs localized by Swift BAT as of this writing, 95% were localized by Swift XRT. Of the remaining 5%, almost all were unable to be observed by Swift XRT for a considerable time after the burst, due to observing constraints (Burrows et al. 2007). Thus, the Swift XRT is providing 3–4′ localizations for almost all burst afterglows. However, of these bursts, only 50% are detected in the optical. And it turns out that very few bursts not detected in the optical have been observed in the NIR. Thus, half of Swift GRBs are lost at this stage. Of the 50% of GRBs whose afterglows are detected in the optical and/or NIR, a redshift is determined for only 26%. This is most often the case because by the time the afterglow is identified, it becomes too faint or the afterglow is intrinsically too faint from the beginning. Of the 26% of GRBs for which a redshift is determined, 12% lie at VHR. And of these, we have NIR spectra for 0%.

Without significant changes, it is clear that the full promise that Swift holds for using long GRBs as powerful probes of the VHR Universe will not be realized.

6. What is to be done?

In the past, there were often only one or two optical spectrographs, and fewer NIR spectrographs, available for near-real-time observations of a burst afterglow. In addition to this there are chances of bad weather, and often only a single
optical spectrograph and no NIR spectrograph could be brought to bear on a particular afterglow. The availability of NIR spectrographs on the VLT, Gemini North and South, Keck I and II, Magellan and Subaru telescopes is increasing. However, a Swift webpage giving the availability of optical—and especially NIR—spectrographs on these large telescopes would better enable the astronomers and observatory directors to make informed decisions about whether to invoke and approve ToO observations of a particular candidate VHR burst.

But optical, and particularly NIR, spectroscopic observations of GRB afterglows are still time consuming, and the amount of time that TACs are willing to allocate to such observations is modest. It is therefore clear that, in order to exploit these resources, a ‘bootstrap’ approach is necessary, in which photometric observations in the optical and NIR must establish that a particular burst has a reasonably high probability of being at VHR before observing programs that use optical and NIR spectrographs on large telescopes will be invoked.

The two major reasons for the paucity of detected VHR GRBs are that (i) NIR afterglows are not being detected early enough for many Swift GRBs and (ii) reasonably strong evidence that a burst may lie at VHR (i.e. the afterglow is not detected to deep limits in the optical and is detected in the NIR) is not being obtained early enough. Thus, we must redouble efforts to observe Swift GRBs rapidly in both optical and NIR using greater than 2 m class telescopes.

Follow-up observations of GRB afterglows in the NIR may also be facilitated by the planned installation of high-resolution NIR spectrographs (e.g. Triplespec) on similar to or exceeding 2 m class telescopes with dedicated or strong GRB ToO observing programs.

Finally, it is clear that the GRB field, particularly the pursuit of VHR GRBs, would benefit from greater cooperation among observers—a difficult challenge in an endeavour that is as competitive and time-critical as is the field of GRB follow-up observations. Larger collaborations might be one possible solution to this problem.
7. Constraining properties of dark energy using GRBs

(a) Long GRBs

Although long GRBs are the most brilliant events in the Universe, their intrinsic luminosities span more than five decades. At first glance, therefore, these events would hardly seem to be promising standard candles for cosmology. However, a relation has been found between the peak energy $E_{\text{peak}}$ of the spectrum in $\nu F_{\nu}$, the isotropic equivalent energy $E_{\text{iso}}$ in the rest frame of the burst source and the time $t_{\text{jet}}$ of the so-called jet break seen in the optical afterglows of many bursts that can be used to make these bursts relative standard candles (Ghirlanda et al. 2004a; Liang & Zhang 2005; Nava et al. 2006), in a way that is completely analogous to the way that Type Ia supernovae can be made relative standard candles. The uncertainty in $E_{\text{iso}}$ using this method is currently approximately 0.25 dex, which is only twice the current uncertainty in the luminosities of Type Ia supernovae. Thus, long GRBs provide a promising way to constrain the properties of dark energy (Dai et al. 2004; Ghirlanda et al. 2004a, 2006; Firmani et al. 2006b).

However, the optical follow-up observations that are needed in order to determine $t_{\text{jet}}$ are difficult and time consuming, setting aside the worry raised by the fact that the X-ray afterglows of Swift GRBs do not exhibit a jet break of the magnitude or at the time when it would be expected, were it due to the GRB jet opening angle (i.e. a geometrical effect; Burrows et al. 2007).

A recent breakthrough in using long GRBs as relative standard candles has been the discovery by Firmani et al. (2006a) of a relation between $E_{\text{peak}}$, $L_{\text{iso}}$ and the emission duration $T_{0.45}$ (Reichart et al. 2001) that is as narrow as the relation between $E_{\text{peak}}$, $E_{\text{iso}}$ and $t_{\text{jet}}$. This is shown in figure 8a, b, which shows the relation between $E_{\text{peak}}$, $E_{\text{iso}}$ and $t_{\text{jet}}$ and between $E_{\text{peak}}$, $L_{\text{iso}}$ and $T_{0.45}$, respectively. This discovery is very important, because it means that all of the burst properties that are needed to make long GRBs relative standard candles can be derived from the prompt gamma-ray emission.

Figure 9 shows the constraints that can be imposed on the properties of dark energy, translated into contours in the ($\Omega_M$, $w_0$)-plane and the ($w_0$, $w_1$)-plane (Firmani et al. 2006c). Despite the small sample size (20 bursts) of long GRBs for which the necessary information is currently available, combining the constraints from Type Ia supernovae and GRBs leads to tighter constraints on $w_0$ and $w_1$, due in part to the different redshift ranges spanned by Type Ia supernovae and GRBs.

In addition, Lamb et al. (submitted a) have recently shown that X-ray flashes (XRFs) probably satisfy this ‘Firmani relation’, something that was never able to be demonstrated for the ‘Ghirlanda relation’ owing to the faintness of the optical afterglows of XRFs. This is illustrated in figure 10. This also represents an important breakthrough, since one needs numerous GRBs at redshifts $z<0.3$ (i.e. in the redshift range where dark energy dominates the dynamics of the Universe), as well as at redshifts $z>1$ (i.e. in the redshift range where dark matter dominates the dynamics of the Universe), because long GRBs (like Type Ia supernovae) are only relative standard candles. Since XRFs appear to satisfy the Firmani relation, they may supply the needed bursts at $z<0.3$. 

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Of comparable significance for the application of GRBs to cosmology is the discovery in 2005 that most short GRBs probably emanate from the mergers of compact object binaries (Barthelmy et al. 2005; Berger et al. 2005; Fox et al. 2005; Gehrels et al. 2005; Hjorth et al. 2005; Villasenor et al. 2005; Covino et al. 2006). Short GRBs are therefore expected to be powerful sources of gravitational waves. Observation of the gravitational waves from such an in-spiralling compact-object binary can enable short GRBs to be used as absolute standard candles (Dalal et al. 2006).

Figure 11 shows the curves of the maximum sampling distance expected for LIGO and Advanced LIGO for any merging neutron star–neutron star binary. Detection of a short GRB gives the time $t_{\text{merger}}$ of the merger, the location (right

$\text{(b) Short GRBs}$

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Figure 10. Locations of three XRFs relative to the ‘Firmani relation’. The redshift of XRF 050215B is not known, so its trajectory as a function of redshift is shown. From Lamb et al. (submitted a).

Figure 11. Detectability of gravitational waves from short GRBs for LIGO and Advanced LIGO. For a compact binary merger detected in gamma rays (i.e. a short GRB), the maximum sampling distance increases to 600 Mpc. From Thorne (2003).
ascension (RA), declination (Dec)) of the burst on the sky, and the inclination angle \( i \) of the binary relative to the plane of the sky. Knowing these four quantities increases the sensitivity—and therefore the maximum sampling distance—of gravitational wave detectors by a factor of 3. This increases the maximum sampling distance from 600 Mpc to 1.3 Gpc (depending on whether the burst occurs directly overhead) and the number of detectable sources by a factor of 30.

The detection of gravitational waves from a short GRB gives the absolute distance \( d_{\text{GRB}} \) to the burst source, since the strength of the gravitational waves produced during the in-spiral phase can be calculated theoretically to high accuracy and compared with the strength of the observed gravitational waves. Thus, short GRBs are absolute standard candles. The accurately known distance \( d_{\text{CMB}} \) to the surface of last scattering of the CMB then means that the accurate determination of \( H_0 = cz/d_{\text{GRB}} \) provides a strong constraint on the properties of dark energy (Dalal \textit{et al}. 2006).

To see this, consider a flat Universe and a constant \( w \), the equation of state parameter of dark energy. Then, \( \Omega_{\text{DE}} = 1 - \Omega_M \), and the only parameters are \( h \), \( \Omega_M \) and \( w \). The CMB provides two of these parameters \( d_{\text{CMB}} \) and \( \Omega_M h^2 \); short GRBs provide the third \( (h) \). An advantage of using short GRBs to constrain the properties of dark energy is that the resulting constraints are not degraded by gravitational lensing, as are those from Type Ia supernovae and long GRBs.

Figure 12 shows the constraints that can be imposed on \( h \) and \( w \) for several different opening angles of the short GRB jet, assuming no systematic errors. As mentioned above, recent observations of short GRBs suggest that the typical opening angle of short GRB jets may be similar to that of the long GRBs (i.e. similar to or below 10\(^\circ\); Berger \textit{et al}. in press). Adopting what may therefore be a conservative value for the typical opening angle of 18\(^\circ\), just 100 short GRBs can give an accuracy of 0.005 in \( h \) and 0.03 in \( w \)!
Figure 13 shows how these constraints translate into contours in the \((\Omega_M, w)\)-plane for two different values of the short GRB jet opening angle. This figure shows that the constraints from short GRBs and Type Ia supernovae are nearly orthogonal, so that when the two methods are combined, the resulting constraint is strong and almost independent of the short GRB jet opening angle.

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