

Cosmological Uses of Gamma-Ray Bursts

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Abstract. Studies of the cosmic gamma-ray bursts (GRBs) and their host galaxies are starting to provide interesting or even unique new insights in observational cosmology. GRBs represent a new way of identifying a population of star-forming galaxies at cosmological redshifts. GRB hosts are broadly similar to the normal field galaxy populations at comparable redshifts and magnitudes, and indicate at most a mild luminosity evolution out to $z \sim 1.5 - 2$. GRB optical afterglows seen in absorption provide a powerful new probe of the ISM in dense, central regions of their host galaxies, complementary to the traditional studies using QSO absorbers. Some GRB hosts are heavily obscured, and provide a new way to select a population of cosmological sub-mm sources, and a novel constraint on the total obscured fraction of star formation over the history of the universe. Finally, detection of GRB afterglows at $z > 6$ may provide a unique way to probe the primordial star formation, massive IMF, early IGM, and chemical enrichment at the end of the cosmic reionization era.

1. Introduction: The Birth of the GRB Cosmology

Ever since the establishment of their cosmological nature (Metzger et al. 1997), and considering their increasingly probable relation to massive star formation (e.g., Paczyński 1998, Totani 1997, etc.), GRBs promised to become new probes of cosmology and galaxy evolution. As the numbers of GRB redshifts and detected hosts and afterglows grow, it becomes possible to use GRBs in new, systematic studies in cosmology. There are now (late 2002) plausible or certain host galaxies found for all but 1 or 2 of the bursts with optical, radio, or x-ray afterglows localised with arcsec precision, and over 30 redshifts measured for GRB hosts and/or afterglows, ranging from 0.25 (or perhaps 0.0085?) to 4.5, with the median $\langle z \rangle \approx 1.0$. GRBs and their afterglows should be readily detectable at large redshifts (Lamb & Reichart 2000).

There are three basic ways of learning about the evolution of luminous matter and gas in the universe. First, a direct detection of sources (i.e., galaxies)

in emission, either in the UV/optical/NIR (the unobscured component), or in the FIR/sub-mm/radio (the obscured component). Second, the detection of galaxies selected in absorption along the lines of sight to luminous background sources, traditionally QSOs. Third, diffuse extragalactic backgrounds, which bypass all of the flux or surface brightness selection effects plaguing all surveys of discrete sources found in emission, but at a price of losing the redshift information, and the ability to discriminate between the luminosity components powered by star formation and powered by AGN. Studies of GRB hosts and afterglows can contribute to all three of these methodological approaches, bringing in new, independent constraints for models of galaxy evolution and of the history of star formation in the universe.

In this review we focus on some of the cosmological aspects of GRBs and their host galaxies. Parts of the present text have also appeared in the reviews by Hurley, Sari & Djorgovski (2003), and Djorgovski et al. (2003). Some of the general issues regarding GRB redshifts and host galaxies have been reviewed previously, e.g., by Djorgovski et al. (2001b, 2002), and many others.

2. GRB Hosts and Galaxy Evolution

The median apparent magnitude of GRB hosts is $R \approx 25$ mag, with tentative detections or upper limits reaching down to $R \approx 29$ mag. The few missing cases are at least qualitatively consistent with being in the faint tail of the observed distribution of host galaxy magnitudes. Down to $R \sim 25$ mag, the observed distribution is consistent with deep field galaxy counts (Brunner, Connolly, & Szalay 1999), but fainter than that, complex selection effects may be playing a role. It can also be argued that the observed distribution should correspond roughly to luminosity-weighted field galaxy counts. The actual distribution would depend on many observational selection and physical (galaxy evolution) effects, and a full interpretation of the observed distribution of GRB host galaxy magnitudes requires a careful modeling (see, e.g., Krumholz, Thorsett, & Harrison 1998; Hogg & Fruchter 1999). The observed visible light (restframe UV) traces an indeterminate mix of recently formed stars and an older population, and cannot be unambiguously interpreted in terms of either the total baryonic mass, or the instantaneous SFR, and their relative importance is a function of redshift.

Spectroscopic measurements provide direct estimates of recent, massive SFR in GRB hosts, from the luminosity of star formation powered recombination lines, notably the [O II] 3727 doublet, $\text{Ly}\alpha$, and Balmer lines (Kennicutt 1998), the UV continuum at $\lambda_{rest} = 1500$ or 2800 \AA (Madau, Pozzetti, & Dickinson 1998). All of these estimators are susceptible to the internal extinction and its geometry, and have an intrinsic scatter of at least 30%. The observed *unobscured* SFR's range from a few tenths to a few $M_{\odot} \text{ yr}^{-1}$. Applying the reddening corrections derived from the Balmer decrements of the hosts, or from the modeling of the broad-band colors of the OTs (and further assuming that they are representative of the mean extinction for the corresponding host galaxies) increases these numbers typically by a factor of a few. All this is entirely typical for the normal field galaxy population at comparable redshifts. However, such measurements are completely insensitive to any fully obscured SFR components, which could be considerably higher.

Equivalent widths of the [O II] 3727 doublet in GRB hosts, which may provide a crude measure of the SFR per unit luminosity (and a worse measure of the SFR per unit mass), are on average somewhat higher (Djorgovski et al. 2001b) than those observed in magnitude-limited field galaxy samples at comparable redshifts (Hogg et al. 1998). One intriguing hint comes from the flux ratios of [Ne III] 3869 to [O II] 3727 lines: they are on average a factor of 4 to 5 higher in GRB hosts than in star forming galaxies at low redshifts (Djorgovski et al. 2001b). Strong [Ne III] requires photoionization by massive stars in hot H II regions, and may represent indirect evidence linking GRBs with massive star formation.

The interpretation of the luminosities and observed star formation rates is vastly complicated by the unknown amount and geometry of extinction. Both observational windows, the optical/NIR (rest-frame UV) and the sub-mm (rest-frame FIR) suffer from some biases: the optical band is significantly affected by dust obscuration, while the sub-mm and radio bands lack sensitivity, and therefore uncover only the most prodigiously star-forming galaxies. As of late 2002, radio and/or sub-mm emission powered by obscured star formation has been detected from 4 GRB hosts (Berger, Kulkarni & Frail 2001; Berger et al. 2002b; Frail et al. 2002). The surveys to date are sensitive only to the ultra-luminous ($L > 10^{12}L_{\odot}$) hosts, with SFR of several hundred $M_{\odot} \text{ yr}^{-1}$, but suggest that about 20% of GRB hosts are ULIRGs.

Given the uncertainties of the geometry of optically thin and optically thick dust, optical colors of GRB hosts cannot be used to make any strong statements about their net star formation activity. The broad-band optical colors of GRB hosts are not distinguishable from those of normal field galaxies at comparable magnitudes and redshifts (Bloom, Djorgovski, & Kulkarni 2001; Sokolov et al. 2001; Chary, Becklin, & Armus 2002; Le Floch et al. 2003). It is notable that the optical/NIR colors of GRB hosts detected in the sub-mm are much bluer than typical sub-mm selected galaxies: the GRB selection may be revealing a previously unprobed population of dusty star-forming galaxies.

The magnitude and redshift distributions of GRB host galaxies are typical for the normal, faint field galaxies (e.g., Schaefer 2000), as are their morphologies (e.g., Odewahn et al. 1998, Bloom, Kulkarni & Djorgovski 2002): they are often compact, and sometimes suggestive of a merger (Djorgovski, Bloom & Kulkarni 2001, Hjorth et al. 2002), but that is not unusual for galaxies at comparable redshifts. The observed redshift distribution of GRBs is also at least qualitatively as expected for an evolving, normal field galaxy population (Mao & Mo 1998).

If GRBs follow the luminous mass, then the expected distribution would be approximated by the luminosity-weighted galaxy luminosity function (GLF) for the appropriate redshifts. The hosts span a wide range of luminosities, with a characteristic absolute restframe B band magnitude $M_{B,*} \approx -20$ mag, approximately half a magnitude fainter than in the GLF at $z \approx 0$, but comensurate with the late-type (i.e., star forming disk) galaxy population at $z \approx 0$ (Madgwick et al. 2002; Norberg et al. 2002). This is somewhat surprising, since one expects that the evolutionary effects would make the GRB host galaxies, with a typical $z \sim 1$, brighter than their descendants today. The GRB host GLF also has a somewhat steeper tail than the composite GLF at $z \approx 0$, but again similar to

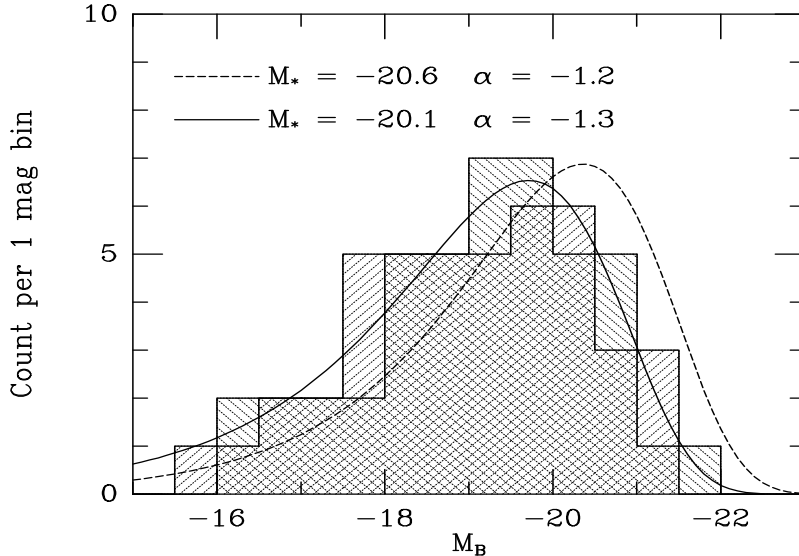


Figure 1. The observed distribution of GRB host galaxy absolute magnitudes in the restframe B band (histograms), fitted by the luminosity-weighted Schechter luminosity function (solid line). The two histograms represent the same data, with the binning offset by half a bin. The dashed line corresponds to the $z \sim 0$ GLF for all morphological types, from the 2df redshift survey.

that of the star-forming, late-type galaxies. This is in a broad agreement with the results of deep redshift surveys which probe the evolution of field galaxy populations out to $z \sim 1$ (Lilly et al. 1995; Fried et al. 2001; Lin et al. 1999), although our understanding of the field galaxy evolution in the same redshift range is still very incomplete. While much remains to be done, it seems that GRB hosts provide a new, independent check on the traditional studies of galaxy evolution at moderate and high redshifts.

3. GRBs as Probes of the Obscured Star Formation

Already within months of the first detections of GRB afterglows, no OT's were found associated with some well-localised bursts despite deep and rapid searches; the prototype “dark burst” was GRB 970828 (Djorgovski et al. 2001a). One explanation is that at least some of these “missing” afterglows are obscured by dust in their host galaxies, which is certainly plausible if GRBs are associated with massive star formation. This is supported by detections of RTs without OTs (e.g., Frail et al. 2000, Taylor et al. 2000). Dust reddening has been detected directly in some OTs (Ramaprakash et al. 1998, Bloom et al. 1998, Djorgovski et al. 1998, etc.); however, this only covers OTs seen through optically thin dust, and there must be others, hidden by optically thick dust. An especially dramatic case was the RT (Taylor et al. 1998) and IR transient (Larkin et al. 1998) associated with GRB 980329 (Yost et al. 2002). We thus know that at least some GRB OTs must be obscured by dust.

This offers a possibility of making a completely new and independent estimate of the mean obscured star formation fraction in the universe. The redshift distribution is not a critical factor here; GRBs are now detected out to $z \sim 4.5$ and that there is no correlation of the observed fluence with the redshift (Djorgovski et al. 2002), so GRBs are, at least to a first approximation, good probes of the star formation over the observable universe.

As of late 2002, there have been ~ 70 adequately deep and rapid searches for OTs from well-localised GRBs, reaching at least to $R \sim 20$ mag within less than a day from the burst, and/or to at least to $R \sim 23 - 24$ mag within 2 or 3 days. In just over a half of such searches, OTs were found. Inevitably, some OTs may have been missed due to an intrinsically low flux, an unusually rapid decline rate (Fynbo et al. 2001; Berger et al. 2002a), or very high redshifts (so that the brightness in the commonly used *BVR* bands would be affected by the intergalactic absorption). Thus the *maximum* fraction of all OTs (and therefore massive star formation) hidden by the dust is $\sim 50\%$.

This is a remarkable result. It broadly agrees with the estimates that there is roughly an equal amount of energy in the diffuse optical and FIR backgrounds (see, e.g., Madau 1999). This is contrary to some claims in the literature which suggest that the fraction of the obscured star formation was much higher at high redshifts. Recall also that the fractions of the obscured and unobscured star formation in the local universe are comparable.

There is one possible loophole in this argument: GRBs may be able to destroy the dust in their immediate vicinity (up to ~ 10 pc?) (Waxman & Draine 2000; Galama & Wijers 2000), and if the rest of the optical path through their hosts (\sim kpc scale?) was dust-free, OTs would become visible. Such a geometrical arrangement may be unlikely in most cases, and our argument probably still applies. A more careful treatment of the dust evaporation geometry is needed, but it is probably safe to say that GRBs can provide a valuable new constraint on the history of star formation in the universe.

4. GRBs as Probes of the ISM in Evolving Galaxies

Absorption spectroscopy of GRB afterglows is now becoming a powerful new probe of the ISM in evolving galaxies, complementary to the traditional studies of QSO absorption line systems. The key point is that the GRBs almost by definition (that is, if they are closely related to the sites of ongoing or recent massive star formation, as the data seem to indicate) probe the lines of sight to dense, central regions of their host galaxies ($\sim 1 - 10$ kpc scale). On the other hand, the QSO absorption systems are selected by the gas cross section, and favor large impact parameters ($\sim 10 - 100$ kpc scale), mostly probing the gaseous halos of field galaxies, where the physical conditions are very different.

The associated GRB absorption systems show exceptionally high column densities of gas, when compared to the typical QSO absorption systems; only the highest column density DLA systems come close (Savaglio, Fall & Fiore 2002, Castro et al. 2003, Mirabal et al. 2002). Lower redshift, intervening absorbers are also frequently seen, and their properties appear to be no different from those of the QSO absorbers. This opens the interesting prospect of using GRB absorbers as a new probe of the chemical enrichment history in galaxies in a

more direct fashion than what is possible with the QSO absorbers, where there may be a very complex dynamics of gas ejection, infall, and mixing at play.

Properties of the GRB absorbers are presumably, but not necessarily (depending on the unknown geometry of the gas along the line of sight) reflecting the ISM of the circum-burst region. Studies of their chemical composition do not yet reveal any clear anomalies, or the degree of depletion of the dust, but the samples in hand are still too small to be really conclusive. Also, there have been a few searches for the variability of the column density of the gas on scales of hours to days after the burst, with no clear detections so far. Such an effect may be expected if the burst afterglow modifies the physical state of the gas and dust along the line of sight by the evaporation of the dust grains, additional photoionization of the gas, etc. However, it is possible that all such changes are observable only on very short time scales, seconds to minutes after the burst. A clear detection of a variable absorption against a GRB afterglow would be an important result, providing new insight into the circumstances of GRB origins.

5. High-Redshift GRBs: A Unique Probe of the Primordial Star Formation and Reionization

Possibly the most interesting use of GRBs in cosmology is as probes of the early phases of star and galaxy formation, and the resulting reionization of the universe at $z \sim 6 - 20$. If GRBs reflect deaths of massive stars, their very existence and statistics would provide a superb probe of the primordial massive star formation and the initial mass function (IMF). They would be by far the most luminous sources in existence at such redshifts (much brighter than SNe, and most AGN), and they may exist at redshifts where there were *no* luminous AGN. As such, they would provide unique new insights into the physics and evolution of the primordial IGM during the reionization era (see, e.g., Lamb & Reichart 2001; Loeb 2002a,b).

There are two lines of argument in support of the existence of copious numbers of GRBs at $z > 5$ or even 10. First, a number of studies using photometric redshift indicators for GRBs suggests that a substantial fraction (ranging from $\sim 10\%$ to $\sim 50\%$) of all bursts detectable by past, current, or forthcoming missions may be originating at such high redshifts, even after folding in the appropriate spacecraft/instrument selection functions (Fenimore & Ramirez-Ruiz 2002; Reichart et al. 2001; Lloyd-Ronning, Fryer, & Ramirez-Ruiz 2002).

Second, a number of modern theoretical studies suggest that the very first generation of stars, formed through hydrogen cooling alone, were very massive, with $M \sim 100 - 1000 M_{\odot}$ (Bromm, Coppi & Larson 1999; Abel, Bryan, & Norman 2000; Bromm, Kudritzki, & Loeb 2001; Bromm, Coppi & Larson 2002; Abel, Bryan & Norman 2002). While it is not yet absolutely clear that some as-yet unforeseen effect would lead to a substantial fragmentation of a protostellar object of such a mass, a top-heavy primordial IMF is at least plausible. It is also not yet completely clear that the (probably spectacular) end of such an object would generate a GRB, but that too is at least plausible (Fryer, Woosley & Heger 2001). Thus, there is some real hope that significant numbers of GRBs and their afterglows would be detectable in the redshift range $z \sim 5 - 20$, spanning the era of the first star formation and cosmic reionization (Bromm & Loeb 2002).

Spectroscopy of GRB afterglows at such redshifts would provide a crucial, unique information about the physical state and evolution of the primordial ISM during the reionization era. The end stages of the cosmic reionization have been detected by spectroscopy of QSOs at $z \sim 6$ (Djorgovski et al. 2001c; Fan et al. 2001; Becker et al. 2001). GRBs are more useful in this context than the QSOs, for several reasons. First, they may exist at high redshifts where there were no comparably luminous AGN yet. Second, their spectra are highly predictable power-laws, without complications caused by the broad Ly α lines of QSOs, and can reliably be extrapolated blueward of the Ly α line. Finally, they would provide a genuine snapshot of the intervening ISM, without an appreciable proximity effect which would inevitably complicate the interpretation of any high- z QSO spectrum: luminous QSOs excavate their Stromgren spheres in the surrounding neutral ISM out to radii of at least a few Mpc, whereas the primordial GRB hosts would have a negligible effect of that type.

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