

The GRB Host Galaxies and Redshifts ^{*}

S.G. Djorgovski¹, S.R. Kulkarni¹, J.S. Bloom¹, D.A. Frail², F.A. Harrison³, T.J. Galama¹, D. Reichart¹, S.M. Castro¹, D. Fox¹, R. Sari⁴, E. Berger¹, P. Price³, S. Yost³, R. Goodrich⁵, and F. Chaffee⁵

¹ Palomar Observatory, Caltech, Pasadena, CA 91125, USA

² NRAO/VLA, Socorro, NM 87801, USA

³ Space Radiation Laboratory, Caltech, Pasadena, CA 91125, USA

⁴ Theoretical Astrophysics, Caltech, Pasadena, CA 91125, USA

⁵ W.M. Keck Observatory, CARA, Kamuela, HI 96743, USA

Abstract. Observations of GRB host galaxies and their environments in general can provide valuable clues about the nature of progenitors. Bursts are associated with faint, $\langle R \rangle \sim 25$ mag, galaxies at cosmological redshifts, $\langle z \rangle \sim 1$. The host galaxies span a range of luminosities and morphologies, and appear to be broadly typical for the normal, evolving, actively star-forming galaxy populations at comparable redshifts and magnitudes, but may have somewhat elevated SFR per unit luminosity. There are also spectroscopic hints of massive star formation, from the ratios of [Ne III] and [O II] lines. The observed, unobscured star formation rates are typically a few M_{\odot}/yr , but a considerable fraction of the total star formation in the hosts may be obscured by dust. A census of detected optical afterglows provides a powerful new handle on the obscured fraction of star formation in the universe; the current results suggest that at most a half of the massive star formation was hidden by dust.

1 Introduction

Host galaxies of GRBs serve a dual purpose: determination of the redshifts, which are necessary for a complete physical modeling of the bursts, and to provide some insights about the possible nature of the progenitors, e.g., their relation to massive star formation, etc.

Table 1 summarizes the host galaxy magnitudes and redshifts known to us as of mid-June 2001. The median apparent magnitude is $R = 24.8$ mag, with tentative detections or upper limits reaching down to $R \approx 29$ mag. Down to $R \sim 25$ mag, the observed distribution is consistent with deep field galaxy counts [56], but fainter than that, selection effects may be playing a role. We note also that the observations in the visible probe the UV in the restframe, and are thus especially susceptible to extinction.

The majority of redshifts so far are from the spectroscopy of host galaxies, and some are based on the absorption-line systems seen in the spectra of the afterglows (which are otherwise featureless power-law continua). Reassuring

^{*} Based in part on the observations obtained at the W.M. Keck Observatory, operated by the California Association for Research in Astronomy, a scientific partnership among Caltech, the Univ. of California and NASA; and with the NASA/ESA Hubble Space Telescope, operated by the AURA, Inc., under a contract with NASA.

Table 1. GRB Host Galaxies and Redshifts (June 2001)

GRB	R mag	Redshift	Type ^a	References ^b
970228	25.2	0.695	e	[25,9]
970508	25.7	0.835	a,e	[48,7,26]
970828	24.5	0.9579	e	[17]
971214	25.6	3.418	e	[39,49]
980326	29.2	~1?		[6], GCN 1029
980329	27.7	<3.9	(b)	GCN 481, 778
980425 ^c	14	0.0085	a,e	[27]
980519	26.2			[29]
980613	24.0	1.097	e	[16]
980703	22.6	0.966	a,e	[15]
981226	24.8			[21]
990123	23.9	1.600	a,e	[40,5]
990308 ^d	>28.5			GCN 726
990506	24.8	1.30	e	[59,8]
990510	28.5	1.619	a	[62], GCN 757
990705	22.8	0.86	x	[47,52]
990712	21.8	0.4331	a,e	[30,31,62]
991208	24.4	0.7055	e	[14], GCN 475, 481
991216	24.85	1.02	a,x	[52], GCN 496, 751
000131	>25.7	4.50	b	[2]
000214		0.37–0.47	x	[3]
000301C	28.0	2.0335	a	[35], GCN 603, 605, 1063
000418	23.9	1.1185	e	GCN 661, 733
000630	26.7			GCN 1069
000911	25.0	1.0585	e	[53]
000926	23.9	2.0369	a	GCN 851, 871
010222	>24	1.477	a	[36], GCN 965, 989, 1002

NOTES:

^a e = line emission, a = absorption, b = continuum break, x = x-ray^b GCN circulars available at http://gcn.gsfc.nasa.gov/gcn/gcn3_archive.html^c Association of this galaxy/SN/GRB is somewhat controversial^d Association of the OT with this GRB may be uncertain

overlap exists in some cases; invariably, the highest- z absorption system corresponds to that of the host galaxy, and has the strongest lines. In some cases no optical transient (OT) is detected, but a combination of the X-ray (XT) and radio transient (RT) unambiguously pinpoints the host galaxy. A new method for obtaining redshifts may come from the X-ray spectroscopy of afterglows, using the Fe K line at ~ 6.55 keV [51,3,52], or the Fe absorption edge at ~ 9.28 keV [65,64,1]. Rapid X-ray spectroscopy of GRB afterglows may become a powerful tool to understand their physics and origins.

Are the GRB host galaxies special in some way? If GRBs are somehow related to the massive star formation (e.g., [60,50], etc.), it may be worthwhile to examine their absolute luminosities and star formation rates (SFR), or spectroscopic properties in general. This is hard to answer [38,34,55] from their visible (\sim restframe UV) luminosities alone: the observed light traces an indeterminate mix of recently formed stars and an older population, cannot be unambiguously interpreted in terms of either the total baryonic mass, or the instantaneous SFR.

The magnitude and redshift distributions of GRB host galaxies are typical for the normal, faint field galaxies, as are their morphologies [32] when observed with the HST: often compact, sometimes suggestive of a merging system [16], but that is not unusual for galaxies at comparable redshifts. Their redshift distribution is about what is expected for an evolving, normal field galaxy population at these magnitude levels. There is an excellent qualitative correspondence between the observations and simple galaxy evolution models [46]. This is further illustrated in Fig. 1, which compares the observed GRB host magnitudes as a function

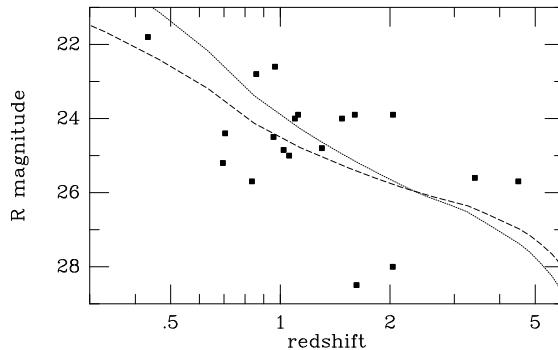


Fig. 1. The R -band Hubble diagram for GRB host galaxies with measured magnitudes and redshifts, as of June 2001. The points represent the hosts; typical error bars are a few tenths of a magnitude. The lines represent Bruzual-Charlot galaxy evolution models [13], normalised to an L_* galaxy today. Both models assume Salpeter IMF, no extinction, galaxy formation redshift $z_{gf} = 6$, and a standard Friedmann cosmology with $h = 0.65$, $\Omega_0 = 0.2$ and $A_0 = 0$. The dotted line corresponds to a model with a constant SFR, and the dashed line to a model with a SFR declining exponentially with an e -folding time of 9.5 Gyr. Allowing for extinction would lower the model curves at higher redshifts; assuming more star formation in the past, and/or a top-heavy IMF would move them higher.

of redshift with stellar population synthesis models which are used to describe the evolution of normal field galaxies. The observed spread of luminosities is reasonable for a normal, evolving galaxy luminosity function.

Fig. 2 shows the distribution of absolute B -band luminosities of GRB hosts identified to date. If GRB's follow the luminous mass, then the expected distribution would be approximated by the luminosity-weighted galaxy luminosity function for the appropriate redshifts. The hosts span a wide range of luminosities, with the sample median very close to a present-day average (L_*) galaxy. The observed distribution can indeed be reasonably described by an evolved Schechter luminosity function, with an overall brightening and a steepening on the low-luminosity end. The interpretation of this result is complex: the observed light reflects an unknown combination of the unobscured fraction of recent star formation (especially in the high- z galaxies, where we observe the restframe UV continuum) and the stellar populations created up to that point.

This is in a qualitative agreement with studies of field galaxy evolution [43,20], which indicate both a brightening of M_* , and a steepening of α , relative to $z \sim 0$ galaxy samples. The apparent frequent occurrence of “subluminous” hosts is not surprising, since most star forming activity at $z \sim 1$ is in starbursting dwarfs (corresponding to the steepening of the power-law tail of the GLF). Thus the GRB hosts seem to be representative of the normal, star-forming field galaxy population at comparable redshifts, and so far there is no evidence for any significant systematic differences between them.

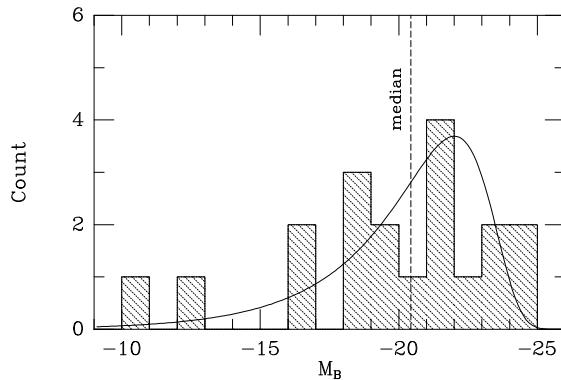


Fig. 2. Distribution of estimated absolute B -band magnitudes for GRB host galaxies with known redshifts, as of June 2001. These restframe magnitudes were computed from the observed R -band magnitudes by approximating the galaxy spectra as $f_\nu \sim \nu^{-1}$ and no additional extinction correction. Standard Friedmann cosmology with $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_0 = 0.2$, and $\Lambda_0 = 0$ was used. The dashed line indicates the sample median, $M_B = -20.43$ mag. The solid curve is a heuristic model, representing a luminosity-weighted Schechter function, with $M_* = -23$ mag and $\alpha = -1.6$. The choice of parameters is meant to be illustrative, rather than a best fit.

One could also speculate that lower luminosity galaxies may on average have lower metallicities, where the mean extinction may be lower, making them easier to detect, or whose stellar IMF may be biased towards more massive stars (this is *highly speculative*).

Within the host galaxies, the distribution of GRB-host offsets follows closely the light distribution [9,11], which is roughly proportional to the density of star formation (especially for the high- z galaxies). It is thus fully consistent with a progenitor population associated with the sites of massive star formation.

Spectroscopic measurements provide direct estimates of the recent, massive SFR in GRB hosts. Most of them are based on the luminosity of the [O II] 3727 doublet [37], the luminosity of the UV continuum at $\lambda_{rest} = 2800 \text{ \AA}$ [44], in one case so far [39] from the luminosity of Ly α 1216 line [39], and in one case [15] from the luminosity of Balmer lines [37]. All of these estimators are susceptible to the internal extinction and its geometry, and have an intrinsic scatter of at least 30%. The observed SFR's range from a few tenths to a few $M_\odot \text{ yr}^{-1}$, again typical for the normal field galaxy population at comparable redshifts.

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 [19] than those observed in magnitude-limited field galaxy samples at comparable redshifts [33]. This is illustrated in Fig. 3. A larger sample of GRB hosts, and a good comparison

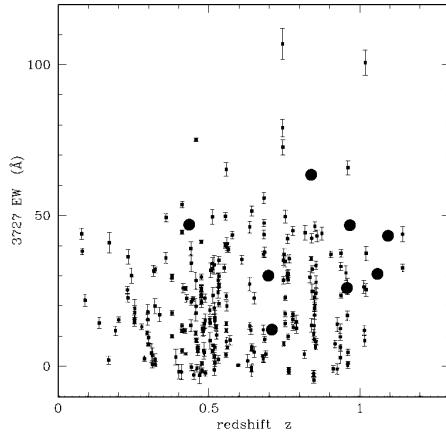


Fig. 3. Restframe equivalent widths of [O II] 3727 line emission for a magnitude-limited sample of field galaxies from Hogg et al. [33] (small squares), and a sample of GRB hosts (large circles). There is a hint that the GRB hosts tend to have higher equivalent widths at comparable redshifts, relative to this field galaxy sample. However, the GRB hosts tend to be fainter on average, as this field sample is magnitude-limited at $R = 23$ mag. The apparent difference in mean equivalent widths may be a combination of sample selection and evolution effects, rather than an evidence for enhanced SFR per unit mass for GRB hosts.

sample, matched both in redshift and magnitude range, are necessary before any solid conclusions can be drawn from this apparent difference.

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. These strong [Ne III] require photoionization by massive stars in hot H II regions, and may represent an 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. The observed quantities (in the visible) trace only the unobscured stellar component, or the components seen through optically thin dust. Any stellar and star formation components hidden by optically thick dust cannot be estimated at all from these data, and require radio and sub-mm observations. Thus, for example, optical colors of GRB hosts cannot be used to make any meaningful 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 [9,57].

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 [17]. Perhaps the most likely explanation for the non-detections of OT's when sufficiently deep and prompt searches are made is that they are obscured by dust in their host galaxies. This is an obvious culprit if indeed GRBs are associated with massive star formation.

Support for this idea also comes from detections of RTs without OTs, including GRB 970828, 990506, and possibly also 981226 (see [59,22]). Dust reddening has been detected directly in some OTs (e.g., [54,4,15] 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 [58] and IR transient [42] associated with GRB 980329. We thus know that at least some GRB OTs must be obscured by dust.

The census of OT detections for well-localised bursts can thus provide a completely new and independent estimate of the mean obscured star formation fraction in the universe. Recall that GRBs are now detected out to $z \sim 4.5$ and that there is no correlation of the observed fluence with the redshift [18], so that they are, at least to a first approximation, good probes of the star formation over the observable universe.

As of mid-June 2001, there have been $\sim 52 \pm 5$ adequately deep and rapid searches for OTs from well-localised GRBs. We define "adequate searches" as 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; this is a purely heuristic, operational definition. The uncertainty comes from the subjective judgement of whether the searches really did go as deep and as fast, and whether the field was at a sufficiently low Galactic latitude to cause concerns about the foreground extinction and confusion by Galactic stars. Out of those, $\sim 27 \pm 2$ OTs were

found (the uncertainty being due to the questionable nature of some candidates). Some OTs may have been missed due to an intrinsically low flux, an unusually rapid decline rate, 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 $(48 \pm 8)\%$.

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., [45]). 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. GRBs can therefore provide a valuable new constraint on the history of star formation in the universe.

There is one possible loophole in this argument: GRBs may be able to destroy the dust in their immediate vicinity (up to ~ 10 pc?) [63,28], 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. Further support for the use of GRBs as probes of obscured star formation in distant galaxies comes from radio and sub-mm detections of the hosts [24,12].

Acknowledgments: We wish to acknowledge the efforts of numerous collaborators worldwide, and the expert help of the staff of Palomar, Keck, and VLA observatories and STScI. This work was supported in part by grants from the NSF, NASA, and private foundations to SRK, SGD, FAH, and RS, Fairchild Fellowships to RS and TJG, Hubble Fellowship to DER, and Hertz Fellowship to JSB.

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