THE FAINT-GALAXY HOSTS OF GAMMA-RAY BURSTS

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ABSTRACT

The observed redshifts and magnitudes of the host galaxies of gamma-ray bursts (GRBs) are compared with the predictions of three basic GRB models, in which the comoving rate density of GRBs is (1) proportional to the cosmic star formation rate density, (2) proportional to the total integrated stellar density, and (3) constant. All three models make the assumption that at every epoch the probability of a GRB occurring in a galaxy is proportional to that galaxy's broadband luminosity. No assumption is made that GRBs are standard candles or even that their luminosity function is narrow. All three rate-density models are consistent with the observed GRB host galaxies to date, although model (2) is slightly disfavored relative to the others. Models (1) and (3) make very similar predictions for host galaxy magnitude and redshift distributions; these models probably will not be distinguished without measurements of host galaxy star formation rates. The fraction of host galaxies fainter than 28 mag may constrain the faint end of the galaxy luminosity function at high redshift, or, if the fraction is observed to be low, may suggest that the bursters are expelled from low-luminosity hosts. In all models, the probability of finding a $z < 0.008$ GRB among a sample of 11 GRBs is less than 10^{-4}, strongly suggesting that GRB 980425, if associated with SN 1998bw, represents a distinct class of GRBs.

Subject headings: galaxies: evolution — gamma rays: bursts — supernovae: individual (SN 1998bw) — X-rays: bursts

1. INTRODUCTION

The study of gamma-ray bursts (GRBs) has been revolutionized by the discovery of extremely well localized X-ray, optical, and radio transients (Costa et al. 1997; van Paradijs et al. 1997; Frail et al. 1997). Follow-up of the optical transients (OTs) has shown that GRBs come from cosmological distances (Metzger et al. 1997b). One notable early result of this follow-up is that the OT host galaxies have generally been near 25th magnitude in the visible for those cases in which a host galaxy has been detected (which is the majority with OTs; see references in Table 1). Five of these host galaxies now have redshifts $z > 0.8$ (Metzger et al. 1997a; Djorgovski et al. 1998a, 1999; Kulkarni et al. 1998a; Bloom et al. 1999). The question considered here is how do the flux and redshift distributions of the GRB hosts compare with the predictions of simple models?

It has been surprising to many that bright GRBs, which have a "Euclidean" number-flux relation suggesting that they are local, are not correlated on the sky with local, bright galaxies (Schaefer 1999; Band & Hartmann 1998). This lack of association has been termed the "no-host problem." Although authors in the no-host literature have generally assumed that the GRB luminosity function is narrow, the lack of correlation at the bright end has suggested, even prior to the recent redshift determinations, that the typical GRB intrinsic energies are very great. The approach taken here is complementary; it is to compute several different host galaxy flux probability distribution functions under the simplest possible assumptions about GRB probability as a function of host galaxy luminosity and redshift and detectability as a function of redshift. The distribution functions are compared with the observations of GRB hosts.

Unfortunately, the association of each GRB with its host requires several steps: the burst is first localized to an accuracy of half to several arcminutes by an X-ray camera. An OT must be discovered in the X-ray error box, sometimes with the help of a prior radio detection. Finally, the OT must decay sufficiently to allow a search for an underlying galaxy. It may not be coincidental that many of the hosts have $R \approx 25$ mag, comparable to the detection limit of a few hours' integration on a large telescope. It is at least possible in one or two cases that the currently associated galaxy is not the host but rather a brighter foreground galaxy at the sky position of the OT by chance. This problem may be compounded by the arcsecond seeing in ground-based telescope images. Despite these caveats, for the purposes of this work the conventionally believed associations of X-ray transients with GRBs, OTs with X-ray transients, and host galaxies with OTs will all be accepted with fawning credulity, as will, of course, the hypotheses that GRBs are cosmological in origin and that they are associated with normal galaxies.

Table 1 lists the GRBs with associated OTs and the positions and extinction-corrected magnitudes of their host galaxies. Magnitudes have been corrected for extinction, and redshifts are given where known. The OT detection associated with GRB 971227 is unconfirmed, and its field was therefore not searched exhaustively for a host galaxy. This nondetection has little impact on the results because, as will be shown below, the limiting magnitude of the search does not put an interesting constraint on its host galaxy, even if the OT detection is good. The host galaxies of GRBs 980326 and 980329 have uncertain magnitudes. The hosts may not be detected, because the light attributed to the hosts may in fact be coming partly from the OTs, even in the latest images. The measured fluxes really ought to be treated as upper limits (Bloom & Kulkarni 1998; Fruchter 1999; E. Pian 1998, private communication). GRB 980425 is excluded from the analysis because, as will be shown below, it is an outlier at the 10^{-4} level in all reasonable models.

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TABLE 1
Host Galaxy Information for GRBs with Associated OTs

GRB	R.A. (2000)	Decl. (2000)	l (deg)	b (deg)	A_R[a] (mag)	R_{corr} (mag)	z	References
970228.......	05 01 46.7	+11 46 53.6	188.91	−17.94	0.58	24.7	...	1
970508.......	06 53 49.4	+79 16 19.6	134.96	+26.73	0.13	25.0	0.835	2, 3
971214.......	11 56 26.0	+65 12 00.0	132.04	+50.94	0.04	26.2	3.418	4, 5
971227[b]......	12 57 10.6	+59 24 43.0	121.57	+57.70	...	>22.0		6
980326.......	08 36 34.0	−18 51 24.0	242.36	+13.04	0.22	>27.1	...	7
980329[c]......	07 02 38.0	+38 50 44.0	178.12	+18.65	0.19	>25.5	...	8
980425[d]......	19 35 03.2	−52 50 46.1	344.99	−27.72	0.16	14.1	0.008	9
980519.......	23 22 21.4	+77 15 43.0	117.96	+15.26	0.71	24.8	...	10
980613[e]......	10 17 57.6	+71 27 26.4	138.06	+40.86	0.23	23.4	1.096	11, 12
980703.......	23 59 06.7	+08 35 07.0	101.48	−52.26	0.15	22.6	0.966	2, 14
990123.......	15 25 30.5	+44 46 00.5	73.12	+54.64	0.04	23.7	1.600[f]	15, 16

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] Extinction values for the R band are based on the reddening maps of Schlegel, Finkbeiner, & Davis 1998.

[b] Included in analysis, although OT detection is uncertain and unconfirmed.

[c] Host galaxy magnitude is considered a limit because it was measured by subtracting extrapolation of fading OT flux; for the purposes of the comparing models and observations, 25.5 mag is adopted in this study.

[d] Excluded from analysis because this burst must come from a distinct class; see text.

[e] Included in analysis, although OT detection is uncertain; S. Thorsett & M. R. Metzger 1998, private communication.

[f] Redshift is uncertain because it is based only on a strong absorption system in the spectrum of the OT.

References.—(1) Fruchter et al. 1998. (2) Bloom et al. 1998. (3) Metzger et al. 1997a. (4) Kulkarni et al. 1998a. (5) Odewahn et al. 1998. (6) Mendez, Ruiz-Lapuente, & Walton 1998. (7) Bloom & Kulkarni 1998. (8) Djorgovski et al. 1998b. (9) Kulkarni et al. 1998b. (10) H. Pedersen 1998, private communication. (11) M. R. Metzger 1998, private communication. (12) Djorgovski et al. 1999. (13) Bloom et al. 1998. (14) Djorgovski et al. 1998a. (15) Fruchter et al. 1999. (16) Bloom et al. 1999.

GRB 980425 must represent a distinct class of bursts. Finally, the association of GRB 980613 with its host galaxy is uncertain, because there is a possibility that no OT was detected at all in this case (S. Thorsett & M. R. Metzger 1998, private communication).

An $(\Omega_M, \Omega_\Lambda) = (0.3, 0.0)$ world model is adopted, except where noted, and all results are independent of the Hubble constant. Magnitudes are given in the R band relative to Vega, with $R = 25$ mag corresponding to $R_{AB} = 25.25$ mag or $f_\nu = 0.29 \, \mu$Jy.

2. FIDUCIAL MODELS

Our procedure is to compare several fiducial models with the data and then discuss the effect of variations in these models on the comparison. The emphasis is on minimizing the total number of assumptions.

In all models, we assume that the probability of a GRB "going off" in a particular galaxy, at a particular epoch, is proportional to that galaxy's broadband luminosity. In the star formation rate (SFR) models, it is assumed that the total comoving rate density (number per unit comoving volume per unit time) at which GRBs are produced at any particular epoch is proportional to the total comoving star formation rate density $\dot\rho(z)$ at that epoch. A by-eye fit was performed to the $\dot\rho(z)$ measurements of Connolly et al. (1997); this fit is shown in the second panel of Figure 1 and has $\dot\rho(z) \propto z^{0.90}$ at redshifts $z < 1.0$, $z^{0.00}$ at $1.0 < z < 2.5$, and $z^{-0.38}$ at $z > 2.5$. In the total stellar density (TSD) models, it is assumed that the comoving rate density is proportional to the total number density of stars that have been formed since the beginning of cosmic time, the integral of the star formation rate density $\int \dot\rho(z)dt$. Finally, in the constant per comoving volume (CCV) model, the comoving rate density is the same at all epochs.

At least some GRBs and OTs can be detected to very high redshift (Kulkarni et al. 1998a). Unfortunately, the

detection function $p_{detect}(z)$, or probability of GRB (and X-ray and OT) detection as a function of redshift z, is unknown empirically and impossible to compute theoretically because it depends not only on the sensitivities of the detectors but on the distribution of intrinsic gamma-ray, X-ray, and optical properties of the bursts, along with the quality and consistency of X-ray and optical follow-up observations. Although it is somewhat unconventional to pack all of the uncertainties about the multivariate gamma-ray, X-ray, and optical GRB luminosity functions and
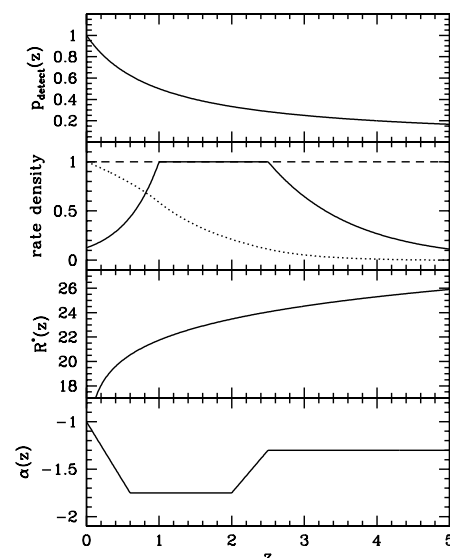

Fig. 1.—Inputs to the fiducial models. *From top to bottom*: Detection function $p_{detect}(z)$ as a function of redshift z; the comoving rate density for the SFR model (*solid line*), TSD model (*dotted line*), and CCV model (*dashed line*); apparent magnitude $R^*(z)$ corresponding to L^* in the observed R band; and the faint-end slope $\alpha(z)$ of the galaxy luminosity function, appropriate for the observed R band.

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detector and follow-up sensitivities into the single function $p_{detect}(z)$, it greatly reduces the total number of assumptions and clarifies the model dependence of the results. Studies of the GRB luminosity function that are consistent with the observed GRB number counts and redshifts suggest that $p_{detect}(z)$ is a weak function of z, falling by only a factor of a few from $z = 1$ to $z = 3$ (Krumholz, Thorsett, & Harrison 1998). Indeed, at least one burst with an associated OT has been associated with a redshift 3.4 host galaxy (Kulkarni et al. 1998a), and it is plausible that GRB 980329 is at $z \sim 5$ (Fruchter 1999). In any event, as discussed below, we find that the results are only significantly affected if $p_{detect}(z)$ is very strongly weighted toward low redshift (corresponding to a GRB or X-ray or OT luminosity function very strongly weighted toward low-energy bursts). For the purposes of the fiducial models, it is simply assumed that $p_{detect}(z) \propto (1 + z)^{-1}$ over the redshift range $0 < z < 5$, and that $p_{detect}(z) = 0$ at $z > 5$, as is shown in the top panel of Figure 1. The function $p_{detect}(z)$ varies slowly out to $z = 5$ because the gamma-ray bursts are not assumed to be standard candles; this analysis allows the luminosity function to be very wide without in fact specifying its width or shape. At $z > 5$, $p_{detect}(z)$ vanishes because Lyman-limit absorption will obscure OTs and host galaxies in the R band. As will be seen below, the results do not depend very strongly on the assumed form of $p_{detect}(z)$.

We assume that all observations of hosts are performed in the R band. Thus the observing band in the frame of the host will vary with redshift. To maintain independence of the world model, the characteristic luminosity L^* appearing in the Schechter (1976) form of the luminosity function is input in the form of the apparent magnitude R^* to which it corresponds at each epoch, which is the directly observed quantity. In practice, the $R^*(z)$ employed is equivalent to $\log L^*$ evolving from 36.5 (in νL_ν in h^{-2} W) at $z = 0$ to 40.0 at $z = 5$ in an $(\Omega_M, \Omega_\Lambda) = (0.1, 0.0)$ universe. [This is not the default cosmology, but this form for $R^*(z)$ is simply a parameterization of the observational determinations, with the (0.1, 0.0) world model used for consistency with Pozetti et al. 1998]. This form of $R^*(z)$ is shown in Figure 1 and is consistent with all measures of luminosity function evolution to $z \sim 1$ (Lilly et al. 1995; Ellis et al. 1996; Hogg 1998) and at $z > 2.5$ (Pozzetti et al. 1998). As shown in Figure 1, the faint-end slope parameter $\alpha(z)$ is chosen to be flat ($\alpha = -1.00$) in the local universe (e.g., Loveday et al. 1992; Lilly et al. 1995; Ellis et al. 1996; Hogg 1998) and slightly steeper ($\alpha = -1.30$) at high redshifts $2.5 < z < 5$ (Pozzetti et al. 1998), and steeper still ($\alpha = -1.75$) in between at redshifts $0.6 < z < 2.0$. This $\alpha = -1.75$ epoch is required to make the steep number counts, which show $d \log N/dm = 0.3$ in the R band at the faint end (Hogg et al. 1997), and in the redshift interval $0.6 < z < 2.0$ there are not yet strong direct constraints on this slope (Lilly et al. 1995; Ellis et al. 1996; Hogg 1998), so this $\alpha(z)$ model, shown in Figure 1, is consistent with all observations. This model is only arbitrary in the choice of redshift interval for the $\alpha = -1.75$ epoch; some such epoch is required in all natural models of the faint galaxy counts.

In the SFR models, the GRB probability will not be strictly proportional to a galaxy's broadband luminosity but rather to its star formation rate. At high redshift, the observed visual luminosity is a very good measure of star formation rate, because observed visual is emitted in the rest-frame ultraviolet. This is less true in the local universe

where star formation is at least somewhat weighted toward lower luminosity galaxies (Small, Sargent, & Hamilton 1997). This effect is not strong, and therefore does not greatly affect the results, but means that the number of bright ($R < 22$) hosts predicted by this procedure may be slightly higher than in a more accurate representation of the SFR model.

3. FIDUCIAL RESULTS AND COMPARISON WITH DATA

The host galaxy flux and redshift distribution predictions of the fiducial models are shown in Figure 2, along with the observed host galaxy magnitudes and redshifts.

The models are compared with relative likelihoods, $\mathcal{L}$, of obtaining the observed host galaxy magnitudes given the model. The likelihoods are computed by multiplying together the differential probability $f(m)$ (probability per unit magnitude) evaluated at each observed host magnitude value, and the integral of $f(m)dm$ from m_{lim} to ∞ for the magnitude limits on GRBs 971227, 980326, and 980329. Unfortunately, likelihoods are only relative, not absolute. The relative likelihoods for the fiducial SFR, TSD, and CCV models are $1.00:0.12:0.57$.

Although clearly all three models are consistent with the observed host galaxy magnitude distribution, both the likelihoods and the appearance of Figure 2 suggest that the TSD model is slightly disfavored relative to SFR and CCV. The likelihood test is not applied to the redshift distribution
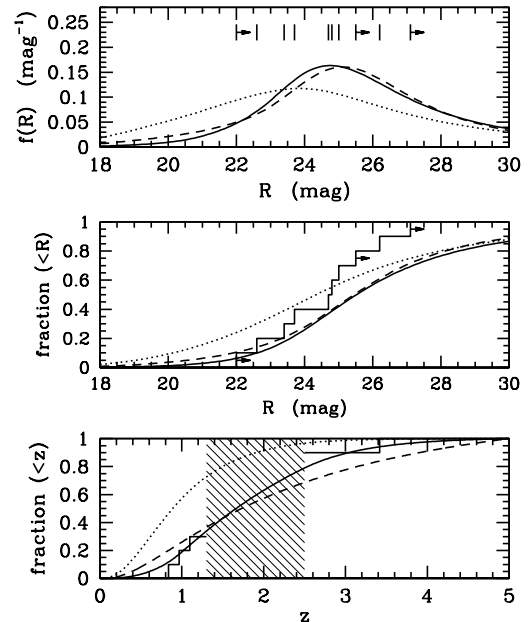

FIG. 2.—Differential distribution of host galaxy magnitudes R (*top panel*), cumulative distributions of host galaxy magnitudes (*middle panel*), and cumulative distribution of host galaxy redshifts z (*bottom panel*) for the fiducial SFR model (*solid line*), TSD model (*dotted line*), and CCV model (*dashed line*). Vertical bars show the observed host galaxy magnitudes, and histograms show the observed cumulative magnitude and redshift distributions. Limits are marked with arrows. The plotted magnitudes have been corrected for extinction. In the redshift plot, it is assumed that all hosts with no redshift lie in the shaded redshift range $1.3 < z < 2.5$, because visual spectroscopy is difficult between the redshift at which the [O II] 3727 Å line leaves the red end of the spectroscopic window and that at which the Lyα 1216 Å line enters the blue. (Note that spectroscopy with large telescopes has been performed on most of the known GRB host galaxies.) The redshift of GRB 990123 is not plotted because it is based on an absorption system in the OT and is therefore both uncertain and not subject to the same selection effects as the emission redshifts.

because there is great uncertainty in the redshift identification probability as a function of magnitude and redshift, which may dominate the shape of the observed redshift distribution. However, under the assumptions about redshift identification probability with which Figure 2 was made, it appears that the host galaxy redshift distribution also slightly disfavors the TSD model.

In all three models, the probability of finding a $z < 0.008$ GRB among a sample of 11 GRBs is less than 10^{-4}, strongly suggesting that GRB 980425, if associated with SN 1998bw, represents a distinct class of GRBs, justifying its exclusion from the analysis. It is worthy to note that this argument for a second class of GRBs makes no reference to the intrinsic energetics of GRB 980425 and is therefore qualitatively different from previous arguments (Kulkarni et al. 1998b).

It is clear from Figure 2 that even with a much larger number of GRB host observations it will be very difficult to distinguish the SFR from the CCV using the magnitude or redshift distributions. Previous claims to the contrary (Totani 1998) are based on an unrealistic assumption that GRBs are close to standard candles. The SFR and CCV models make very similar predictions because the comoving rate densities only differ significantly at low redshift, where there is not much comoving volume, and at high redshift, where the time dilation $(1 + z)$ factor, which comes into rate calculations, and the declining $p_{detect}(z)$ both effectively reduce the contribution to the total GRB rate. The two hypotheses will be readily distinguishable by investigating the spectral properties of the associated hosts; the SFR models predict bluer and more emission-line–dominated galaxies than an average sample. It does appear that the majority of GRB hosts do show signs of fairly active star formation (Kulkarni et al. 1998a; Metzger et al. 1997a; Fruchter et al. 1998); there may already be enough information about host galaxies to distinguish these models. Another simple hypothesis that would make very similar predictions to the SFR is that the comoving rate density is proportional to the evolving number density of quasars (e.g., Schmidt, Schneider, & Gunn 1995).

Previous no-host studies have claimed to rule out interesting GRB models with limits on host galaxies in the range 13–23 mag (Schaefer 1999; Band & Hartmann 1998), but such studies do not strongly constrain the GRB models presented here. There may be no contradiction, because the previous literature on the no-host problem is primarily concerned with very bright bursts, and a narrow or standard-candle GRB luminosity function usually has been assumed. The present analysis, which does not specify a GRB luminosity function but allows it to be very wide, is not capable of making different predictions for the host galaxies of bursts with different observed fluences. This analysis sacrifices that capability in order to avoid making unnecessary assumptions.

4. VARIATION WITH INPUTS

Not surprisingly, the predictions do not depend strongly on cosmology. In an $(\Omega_M, \Omega_\Lambda) = (1.0, 0.0)$ universe, the SFR, TSD, and CCV models have likelihoods of 1.00: 0.06: 0.45. In an $(\Omega_M, \Omega_\Lambda) = (0.4, 0.6)$ universe, they have 1.00: 0.12: 0.57.

Unfortunately, the results do depend somewhat on the choice of p_{detect}, the least well constrained of the model inputs. If $p_{detect}(z) = 1$ is adopted, the SFR, TSD, and CCV models have likelihoods of 1.00: 0.23: 0.58. If $p_{detect}(z) = (1 + z)^{-3}$ is adopted, they have 1.00: 0.03: 0.23. Weighting $p_{detect}(z)$ toward high redshift improves the success of the TSD model relative to the SFR and CCV models, because the TSD rate density itself is weighted toward low redshift. However, $p_{detect}(z) = 1$ is clearly an unrealistic model; it says that GRBs (and X-ray transients and OTs) are equally easy to detect at all redshifts! Conversely, strong weighting of $p_{detect}(z)$ toward low redshift improves the success of SFR and CCV relative to TSD. Even in the $p_{detect}(z) = (1 + z)^{-3}$ models, the probability of finding a $z < 0.008$ GRB among this sample of 11 is still very small.

There is some debate about the rise of the star formation rate density with cosmic time at high redshift, since the measurements are subject to possible incompleteness and uncertain dust extinction corrections (e.g., Pettini et al. 1998). This uncertainty is not important here; if the rise in the star formation rate with time at $z > 2.5$ is replaced with a constant value equal to the value at $z > 1.0$ (which may more accurately represent the true situation; C. C. Steidel & K. L. Adelberger 1998, private communication), the likelihoods for the SFR, TSD, and CCV models become 1.00: 0.20: 0.64. It is worthy to note that this change makes the SFR and CCV models even more difficult to distinguish than in the fiducial case.

The uncertain high-redshift faint-end slope of the galaxy luminosity function does affect the results. If it is changed to $\alpha(z) = -1.75$ for all redshifts $z > 2.0$, which is probably still consistent with the existing $z \sim 3$ galaxy observations (Pozzetti et al. 1998), the SFR, TSD, and CCV models have likelihoods of 1.00: 0.29: 0.41. The relative success of TSD is improved when the luminosity function is made more dwarf-rich. However, the fraction $F_{>28}$ of hosts predicted to be at $R > 28$ mag (i.e., extremely faint) becomes large. Quantitatively, as the $z > 2.5$ value of α ranges from -1.0 to -1.75, $F_{>28}$ for the SFR, TSD, and CCV models ranges from $F_{>28} = 0.21$, 0.19, and 0.17 to 0.34, 0.22, and 0.35. If the faint end of the galaxy luminosity function really is steep at high redshift, and either the SFR or the CCV hypothesis is close to correct, it is possible that some of the current GRB host galaxy identifications or photometric measurements are in error, since very few optical observations are sensitive to 28 mag.

In all of these models, a large fraction of host galaxies have extremely small intrinsic luminosities. Even if such galaxies are as common as the extrapolated galaxy luminosity functions suggest, they may not host GRBs. For example, in neutron star–neutron star merger scenarios, very low mass galaxies do not gravitationally bind kicked neutron star binaries (Bloom, Sigurdsson, & Pols 1998c). For this reason it might be sensible to implement a low-luminosity cutoff to the galaxy luminosity function. With a cutoff at 10^{-2} L^*, the SFR, TSD, and CCV models have likelihoods 1.00: 0.04: 0.58, and $F_{>28}$ drops to 0.030, 0.0068, and 0.044. Furthermore, the dependence of the results on the faint-end slope of the luminosity function at high redshift disappears almost entirely.

5. SUMMARY

The expected distribution of GRB host galaxy fluxes and redshifts are predicted, assuming reasonable GRB comoving rate density models and that at any epoch GRB probability is proportional to host galaxy luminosity. The analysis makes fewer assumptions than previous studies. In

particular, it makes no assumption of a narrow GRB luminosity function. The agreement between the models and the data, for reasonable choices of model parameters, is very good. Of the three models considered, the TSD fares worst, although it is by no means ruled out. The SFR and CCV models make very similar predictions for the host galaxy magnitude and redshift distributions, so those two models will have to be distinguished with observations of host galaxy SFRs.

We do not find a classical no-host problem in the sense of a lack of local, bright galaxy hosts, although as stated above the present analysis does not make different predictions for bursts of different fluences. There may be some suggestion that GRBs do not occur in extremely low luminosity host galaxies, because when no cutoff is applied to the luminosity function at low luminosity, the models predict a significant fraction of GRB hosts below the detection limits of typical surveys. Of course it is possible that up to three of the current hosts fall into this category in the current sample of GRBs with OTs.

One conclusion of this work is that GRB 980425, associated with the low-redshift SN 1998bw, must be a member of a distinct class. In all models, the probability of finding a $z < 0.008$ GRB among a sample of 11 GRBs is less than 10^{-4}.

It is notable that in the models presented here, many GRBs and their hosts lie in the redshift range $1.3 < z < 2.5$, where galaxies are very hard to identify with visual spectroscopy, even on large telescopes. Either infrared spectroscopy or the ultraviolet capabilities of the *Hubble Space Telescope* may be necessary to obtain the redshifts of these GRBs.

NOTE ADDED IN MANUSCRIPT.—The first version of this paper was submitted when all known GRB host magnitudes (except GRB 980425) were in the range $24.4 < R < 25.8$ mag. At that time, the largest discrepancy between the observations and the models was that the width of the observed magnitude distribution was much narrower than the prediction of any model. Since then, three host magnitude measurements (971214, 980326, and 980613) have been significantly revised (Odewahn et al. 1998; Bloom & Kulkarni 1998; M. R. Metzger et al. 1998, private communication), and two new host magnitudes (980703 and 990123) have been measured (Bloom et al. 1998; Fruchter et al. 1999), greatly improving the agreement between the models and the data.

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