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Why Are Gamma-Ray Bursters in Faint Galaxies? Implications for the Bursts and Their Hosts

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WHY ARE GAMMA-RAY BURSTERS IN FAINT GALAXIES? IMPLICATIONS FOR THE BURSTS AND THEIR HOSTS.

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ABSTRACT

With one exception, the host galaxies associated with GRBs observed to date lie in the magnitude range $24.4 \leq R \leq 25.8$. Here we compare the observed redshifts and magnitudes of the host galaxies with the predictions of three basic models: 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. At any epoch, the probability of a GRB occuring in a galaxy is assumed to be proportional to that galaxy's broad-band luminosity. No assumption is made of standard candles or even a narrow GRB luminosity function. The integrated stellar density model is ruled out. The star formation and constant models are consistent with the observed GRB host galaxies to date; these two models make very similar predictions for host magnitudes and redshifts but can be distinguished by the average spectral properties of the host galaxies. The peak in the distribution of host magnitudes in these models is predicted to be near 25 mag, but the width of the distribution in any model is broader than the observed width; this suggests that some associations of GRBs with hosts may be spurious. All models predict that at least a third of future host galaxy detections will be brighter than 24 mag. The fraction fainter than 26 mag constrains the faint end of the galaxy luminosity function at high redshift, if the bursters are not expelled from low-luminosity hosts. In all models, the probability of finding a $z < 0.008$ GRB among a sample of ten GRBs is less than 10^{-4}, strongly suggesting that GRB 980425, if associated with supernova 1998bw, represents a distinct class of GRBs.

Subject headings: galaxies: evolution — gamma rays: bursts — supernovae: individual (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 twenty-fifth magnitude in the visible, for those cases in which a host galaxy has been detected (which is the majority with OTs; references in Table 1). Three of these host galaxies now have large redshifts, 0.835, 0.966, and 3.418 (Metzger et al 1997a, Djorgovski et al 1998d, Kulkarni et al 1998). The question considered here is: *What flux and redshift distributions are expected for the GRB hosts?*

It has been surprising to many, however, 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 1998, Band & Hartmann 1998). This lack of association has been termed the "no-host problem." Although these authors 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 about the detectability of the GRB as a function of redshift. These distribution functions can be compared with the observations, either to discriminate scenarios or else to bolster or undermine confidence in a host-galaxy identification.

Unfortunately, the association of each GRB with its host is not direct; in each case a time-variable x-ray source in the large gamma-ray positional error box is associated with the GRB, the few-square-arcmin x-ray error box is searched for a variable point source in the optical or radio, which is associated with the coincident faint galaxy in the optical. It is non-trivial to identify the correct host galaxy; it may not be coincidental that the hosts have $R \approx 25$ mag, comparable to the detection limit of a few hours' integration on a large telescope. The possibility that some associations are spurious will be discussed below. 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 all GRBs are cosmological in origin, and that they are associated with normal galaxies.

Table 1 lists the GRBs with associated OTs and what is known about their host galaxies. Magnitudes have been corrected for extinction, and redshifts are given where

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known. As mentioned above, it is striking that the host galaxies of OTs associated with GRBs all have $24.3 < R < 25.8$ mag, except for GRB 971227 and GRB 980703 which have not been searched exhaustively for a host, and GRB 980425, associated with nearby supernova 1998bw. GRB 971227 and GRB 980703 have no impact on the results because, as will be shown below, the limiting magnitudes of the searches do not put interesting constraints on their host galaxies. GRB 980425 is excluded from the analysis because, as will also be shown below, it is an outlier at the 10^{-4} level in all reasonable models. GRB 980425 must represent a distinct class of bursts.

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 m are given Vega-relative in the R band, with $R = 25$ mag corresponding to $R_{\rm AB} = 25.25$ mag or $f_\nu = 0.29\ \mu$Jy.

2. FIDUCIAL MODELS

The procedure will be to compare several fiducial models with the data and then discuss the effect of variations in these models on the comparison. In all models, we assume that the probability of a GRB "going off" in a particular galaxy, at a particular epoch, is proportion to that galaxy's broad-band 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 emitted at any particular epoch is proportional to the total 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, it 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 which 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 1998). Unfortunately, the detection function $p_{\rm detect}(z)$, or probability of GRB (and X-ray and OT) detection as a function of redshift, 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. Studies of the GRB luminosity function which are consistent with the observed GRB number counts and redshifts suggest that $p_{\rm detect}$ is a weak function of redshift z, falling by only a factor of a few from $z = 1$ to $z = 3$ (Krumholz, Thorsett & Harrison 1998). Furthermore, at least one burst with an associated OT has been associated with a redshift 3.4 host galaxy $z > 3$ (Kulkarni et al 1998). In any event, the results are not greatly affected by the detection function unless it is very strongly weighted towards low redshift (corresponding to a GRB luminosity function very strongly weighted towards low-energy bursts). For the purposes of the fiducial models it is simply assumed that $p_{\rm detect}(z) \propto (1+z)^{-1}$ over the redshift range $0 < z < 5$ and $p_{\rm detect}(z) = 0$ at $z > 5$, as shown in the top panel of Figure 1. The function $p_{\rm detect}(z)$ 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 $z > 5$ $p_{\rm detect}(z)$ 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 strongly on the assumed form of $p_{\rm detect}(z)$.

We assume that all observation 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 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 $m^*(z)$ 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 form of $m^*(z)$ 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 (eg, 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 $\alpha \equiv -1.75$ 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 1996), 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 broad-band luminosity but rather to its star formation rate. At high redshift, the observed visual luminosity is a very good measure of star formation rate. This is less true in the local Universe where star formation is at least somewhat weighted towards lower-luminosity galaxies (Small et al 1997). This effect is not strong and therefore does not strongly affect the results but means that our predictions for the number of bright ($R < 22$ mag) hosts might be slightly too high.

More important than the specific form for the galaxy luminosity function is the low-luminosity cut-off. In principle, no such cut-off is required, since the integral luminosity density is finite at all epochs. However, because the luminosity function is fairly steep at most epochs, the luminosity distribution of typical hosts at each redshift tends to be very broad if no cut-off is employed. Because, in part, this work is aimed at explaining the narrow distribution of host magnitudes, in the fiducial models a low-luminosity cut-off of $10^{-2}\, L^*$ is employed. Furthermore, there is a theoretical motivation for cutting off the luminosity function at the faint end: in neutron-star–neutron-star merger scenarios, very low-mass galaxies do not gravitationally bind kicked neutron-star binaries (Bloom, Sigurdsson & Pols 1998a). The effect of changing this cut-off is discussed

below; primarily it changes the fraction of host galaxies which lie below the detection limit of practical ground-based optical searches.

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 assumption has been made that all hosts with no redshift lie in the 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 that that at which the Lyα 1216 Å line enters the blue. Spectroscopy with large telescopes has been performed on most or all of the known GRB host galaxies.

In what follows, models will be described by three quantities $(F_{<24}, F_{>26}, p_{\rm KS})$, where $F_{<24}$ is the fraction of hosts expected at magnitudes $R < 24$ mag, $F_{>26}$ is the fraction at $R > 26$ mag, and $p_{\rm KS}$ is the probability of the Kolmogorov-Smirnov statistic (Press et al 1992) being larger than it is for the distribution of host magnitudes. More discrepant model and observed distributions have lower values of $p_{\rm KS}$. Since all hosts considered here lie between these magnitudes, a model with a large $F_{<24}$ is subject to a no-host problem. Conversely, a model with a large $F_{>26}$, if correct, suggests that some of the current host galaxy associations are spurious. $R \approx 26$ mag is the effective limit of most optical searches performed so far; therefore fainter hosts would have gone undetected and the observer may have associated the OT to a galaxy which is nearby on the sky, but physically unrelated.

The SFR, TSD, and CCV models have $(F_{<24}, F_{>26}, p_{\rm KS}) = (0.36, 0.24, 0.091), (0.61, 0.11, 0.0014)$, and $(0.37, 0.26, 0.091)$. The TSD model is disfavored. For the SFR and CCV models, there is a marginal no-host problem (about three of the hosts should be at $R < 24$ mag), and one or two of the host associations may be spurious. Because the numbers are small, the SFR and CCV models are not ruled out, but these models all predict that at least a third of future GRB hosts ought to have $R < 24$ mag, and that a tenth or more ought not have hosts at all to a limit of $R = 26$ mag.

In all models, the probability of finding a $z < 0.008$ GRB among a sample of ten GRBs is less than 10^{-4}, strongly suggesting that GRB 980425, if associated with supernova 1998bw, represents a distinct class of GRBs, and justifying its exclusion from the analysis. It is worthy of 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 almost impossible 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 $p_{\rm detect}(z)$ both effectively reduce the true comoving volume. The two hypotheses will only be 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 1998, Metzger et al 1997a, Fruchter et al 1998); there may already be enough information about host galaxies to distinguish these models. Another simple hypothesis which would make very similar predictions to the SFR is that the comoving rate density is proportional to the evolving number density of quasars (eg, 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 to 23 mag (Schaefer 1998, 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 has usually 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.

None of the models explain the narrow distribution of observed host magnitudes. In 10^5 realizations of 7 host galaxy magnitudes from the fiducial SFR, TSD, and CCV model distributions, only 167, 32, and 110 produced all 7 magnitudes within 1.4 mag of one another. A prediction of all models is that as more GRB hosts are discovered, the width of the observed distribution will increase by a factor of a few.

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 $(F_{<24}, F_{>26}, p_{\rm KS}) = (0.42, 0.20, 0.036), (0.69, 0.08, 0.0003)$, and $(0.47, 0.19, 0.019)$. In an $(\Omega_M, \Omega_\Lambda) = (0.4, 0.6)$ universe, they have $(F_{<24}, F_{>26}, p_{\rm KS}) = (0.39, 0.22, 0.058)$, $(0.63, 0.10, 0.00096)$, and $(0.42, 0.22, 0.046)$.

The predicted fractions at $R < 24$ and $R > 26$ mag do depend on the form of $p_{\rm detect}(z)$, but no choice of $p_{\rm detect}(z)$ can make the predicted distribution of host magnitudes narrow like the observed distribution. If $p_{\rm detect}(z) = 1$ is adopted, the SFR, TSD, and CCV models have $(F_{<24}, F_{>26}, p_{\rm KS}) = (0.31, 0.27, 0.18), (0.54, 0.14, 0.0052)$, and $(0.27, 0.32, 0.26)$. If $p_{\rm detect}(z) = (1 + z)^{-3}$ is adopted, they have $(F_{<24}, F_{>26}, p_{\rm KS}) = (0.51, 0.16, 0.0090)$, $(0.75, 0.05, 7.7 \times 10^{-5})$, and $(0.61, 0.12, 0.0015)$. Naturally, a $p_{\rm detect}(z)$ which is strongly weighted to low redshift worsens the no-host problem, reduces $p_{\rm KS}$, and is therefore disfavored. (Even in these extreme models, the probability of finding a $z < 0.008$ GRB among this sample of ten is still vanishingly 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 (eg, Pettini et al 1998). This uncertainty is not important here; if the rise in the star formation rate at $z > 2.5$ is replaced with a constant value equal to the value at $z > 1.0$, the SFR and

TSD models have $(F_{<24}, F_{>26}, p_{\rm KS}) = (0.30, 0.29, 0.21)$ and $(0.57, 0.13, 0.0034)$.

The uncertain high-redshift faint-end slope of the galaxy luminosity function is also not important in the fiducial models. 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 $(F_{<24}, F_{>26}, p_{\rm KS}) = (0.34, 0.31, 0.14), (0.61, 0.12, 0.0015)$, and $(0.35, 0.34, 0.14)$. On the other hand, the spurious-host problem gets more serious, and the dependence of the results on the faint-end slope becomes stronger, if the low luminosity cut-off is made fainter. Lowering or removing this cutoff is appropriate in models in which GRBs go off promptly during star formation (eg, Paczynski 1998), because the probability of a GRB occuring in a particular galaxy will be strictly proportional to star formation rate, which, at redshifts $z > 2$, ought to be strictly proportional to observed visual luminosity. If the cut-off is moved to $10^{-4}\,L^*$, the models have $(F_{<24}, F_{>26}, p_{\rm KS}) = (0.29, 0.38, 0.14)$, $(0.50, 0.28, 0.017)$, and $(0.30, 0.38, 0.15)$. When the cutoff is set at $10^{-4}\,L^*$, the fraction $F_{>26}$ becomes a measure of the faint end slope $\alpha(z)$ at high redshift. Quantitatively, for the SFR and CCV models, $F_{>26}$ ranges from 0.34 and 0.32 to 0.49 and 0.50 as the $z > 2.5$ value of α ranges from -1.0 to -1.75. In the other direction, the cut-off cannot be moved much brighter than $10^{-2}\,L^*$ given the known host luminosity of GRB 970508 (Metzger et al 1997a, Pian et al 1998), but even if it is moved to $10^{-1}\,L^*$, the models have $(F_{<24}, F_{>26}, p_{\rm KS}) = (0.54, 0.06, 0.0028)$, $(0.82, 0.01, 1.0 \times 10^{-5})$, and $(0.52, 0.11, 0.0065)$, making the no-host problem severe. Because, for reasonable values, choices of the faint-end cut-off and slope have their strongest effects on $F_{>26}$, they mainly impacts the spurious-host problem.

5. DISCUSSION

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. We do not find a classical no-host problem, in the sense of a lack of local, bright galaxy hosts. However, there is a marginally significant lack of galaxies with hosts in the range $21 < R < 24$ mag. In most reasonable models, there is also a suggestion that some fraction of the currently associated hosts have been associated in error because several ought to be below the detection limits of typical surveys.

One conclusion of this work is that GRB 980425, associated with the low-redshift supernova 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 ten GRBs is less than 10^{-4}.

All models predict that at least a third of GRB host galaxies will have $R < 24$ mag, and that a tenth or more will have $R > 26$ mag. 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. The ultraviolet capabilities of the Hubble Space Telescope may be necessary to obtain the redshifts of these GRBs.

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TABLE 1
HOST GALAXY INFORMATION FOR GRBS WITH ASSOCIATED OTS

GRB	RA (2000) (h m s)	Dec (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	0.65	24.6		Fruchter et al (1998)
970508	06 53 49.4	+79 16 19.6	134.96	+26.73	0.17	25.8	0.835	Pian et al (1998), Metzger et al (1997a)
971214	11 56 26.0	+65 12 00.0	132.04	+50.94	0.01	25.5	3.418	Kulkarni et al (1998a)
971227	12 57 10.6	+59 24 43.0	121.57	+57.70		> 22.		Mendez, Ruiz-Lapuente & Walton (1998)
980326	08 36 34.0	−18 51 24.0	242.36	+13.04	0.20	25.3		Djorgovski et al (1998a)
980329	07 02 38.0	+38 50 44.0	178.12	+18.65	0.31	25.4		Djorgovski et al (1998b)
980425[b]	19 35 03.2	−52 50 46.1	344.99	−27.72	0.05	14.3	0.008	Kulkarni et al (1998b)
980519	23 22 21.4	+77 15 43.0	117.96	+15.26	0.85	24.7		H. Pedersen, private communication
980613	10 17 57.6	+71 27 26.4	138.06	+40.86	0.07	24.4		Djorgovski et al (1998c)
980703	23 59 06.7	+08 35 07.0	101.48	−52.26		> 22.	0.966	Bloom et al (1998b), Djorgovski et al (1998d)

[a]Extinction values for the R band are based on the reddening maps of Burstein & Heiles (1982).

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

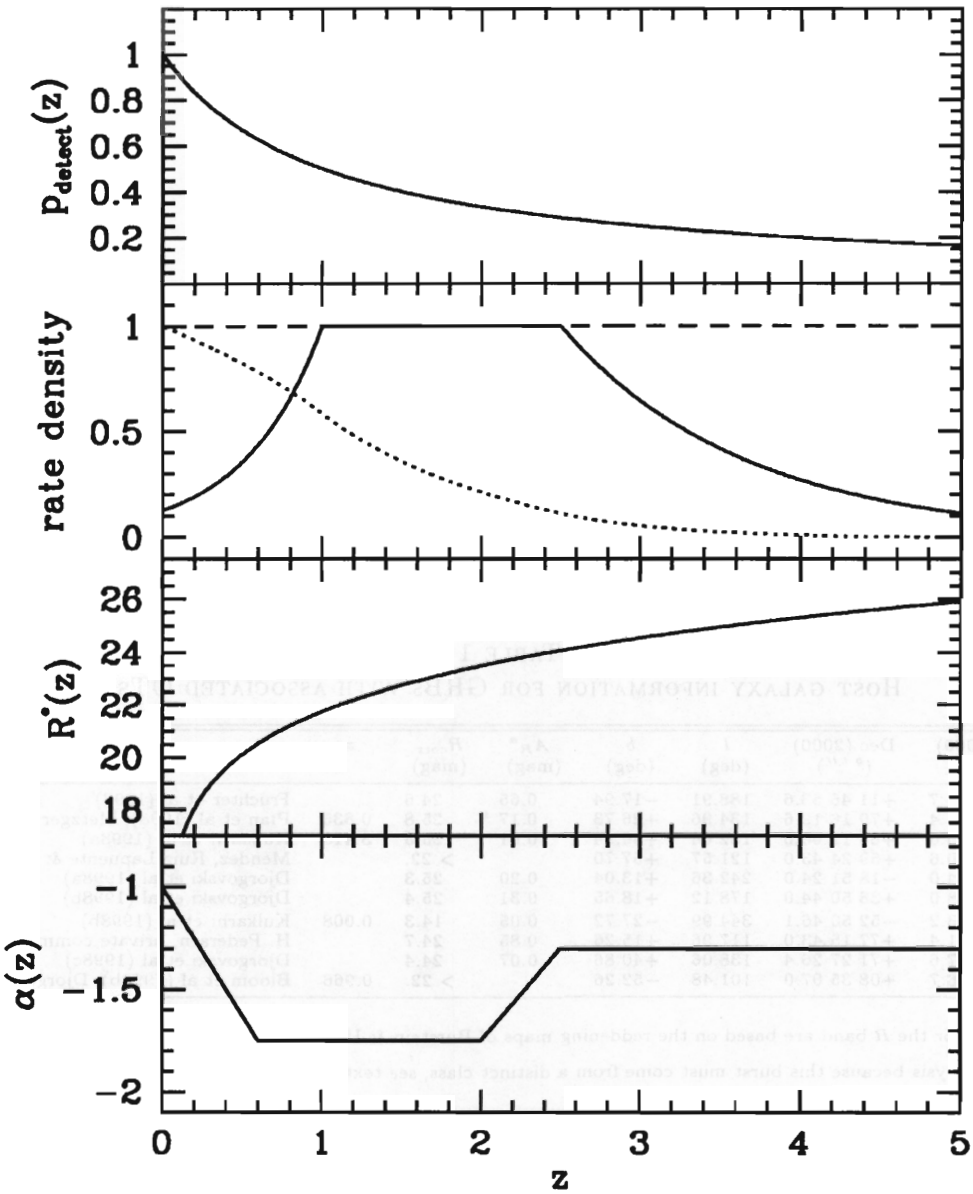

FIG. 1.— The inputs to the fiducial models: *(top)* the detection function $p_{\rm detect}(z)$ as a function of redshift z, *(second)* the comoving rate density for the SFR model *(solid)*, TSD model *(dotted)* and CCV model *(dashed)*, *(third)* the apparent magnitude $R^*(z)$ corresponding to L^* in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

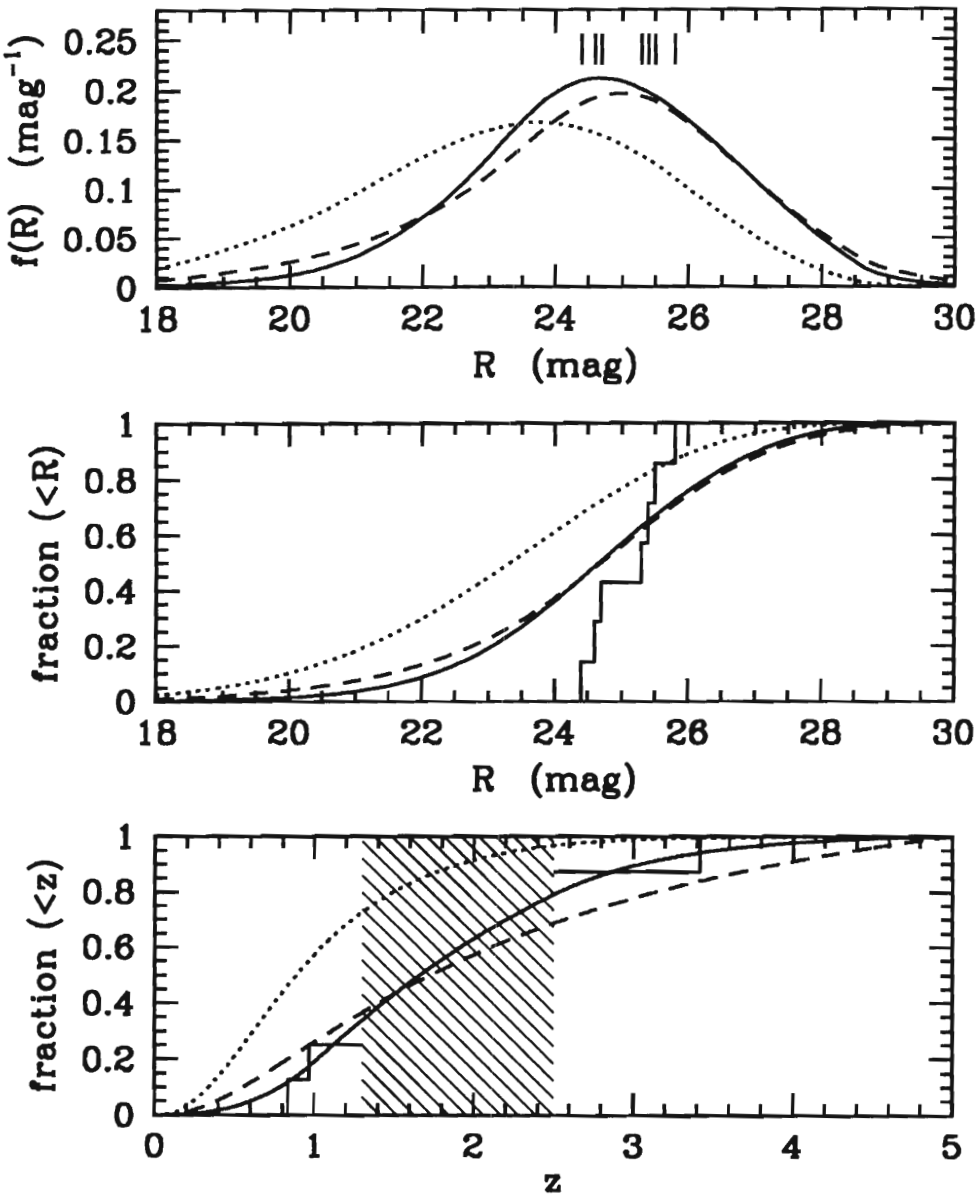

FIG. 2.— The differential distribution of host galaxy magnitudes R *(top)*, cumulative distributions of host galaxy magnitudes *(middle)*, and cumulative distribution of host galaxy redshifts z *(bottom)*, for the fiducial SFR model *(solid)*, TSD model *(dotted)* and CCV model *(dashed)*. Vertical bars show the observed host galaxy magnitudes, histograms show the observed cumulative magnitude and redshift distributions. 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 $1.3 < z < 2.5$ (see text).