Astron. Astrophys. 339, L1–L4 (1998)

ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

The nature of the host galaxies for gamma-ray bursts

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Received 21 August 1998 / Accepted 31 August 1998

Abstract. It has been suggested recently that the rate of gamma-ray bursts (GRBs) is proportional to the star formation rate in the universe. In this paper, we study the nature of GRB hosts expected in this scenario. We improve upon previous studies by incorporating a luminosity function for the GRBs, as required by observations. This model provides a good match to the observed number counts of GRBs as a function of peak-count rate. The model predicts that the host galaxies have their redshift distribution peaked around $z \sim 1$, and about 15 percent have $z > 2.5$. This high-redshift fraction have the same properties as the star-forming galaxies recently discovered by the Lyman-break technique. At $z \lesssim 1$, many of the GRBs may be hosted by faint blue galaxies. Using a photometric redshift sample of galaxies from the Hubble Deep Field, we find that the host galaxies have magnitudes in the range from 21.5 to 28 in the I-band, and about 90 percent of them have semi-major axis smaller than $1.3''$. Assuming isotropic emission, the typical peak-luminosity and total energy of GRBs are $\sim 10^{51} \mathrm{erg\,s^{-1}}$ and $10^{52}\mathrm{erg}$ in an Einstein-de Sitter universe with $H_0 = 100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. We also discuss further observational tests of this scenario.

Key words: gamma-ray: bursts – galaxies: evolution – galaxies: formation – galaxies: starbursts

1. Introduction

The recent redshift measurements of the optical counterparts associated with gamma-ray bursts (GRBs) have established their cosmological origin (e.g. Paczyński 1986). Although the light curves of GRB afterglows can be well accommodated in the relativistic fireball model (e.g., Waxman 1997) the nature of their hosts remains a mystery.

Before the discovery of the optical counterparts, the hosts were thought to be at modest redshift ($z < 1$). This conclusion was based on the simple assumption that the comoving rate of GRBs is a constant (e.g., Mao & Paczyński 1992; Piran 1992; Dermer 1992). However, there is now considerable evidence that the hosts of GRBs may be at substantially higher redshift, both from the redshift measurement for GRB 971214 ($z = 3.42$, Kulkarni et al. 1998) and (indirectly) from the time dilations of GRBs (Fenimore & Bloom 1995; Bonnell et al. 1997). Recent attention has therefore been focused on models in which burst activity is linked to the massive star formation, as would be expected in the "failed-supernova" model (Woosley 1993) or in the "hypernova" model (Paczyński 1998). Totani (1997, 1998) and Wijers et al. (1998) have studied whether such a scenario is consistent with the observed number counts of GRBs as a function of peak-count rate. All these studies assumed that GRBs are standard candles (i.e. they have the same intrinsic luminosity) and were based on the star formation history given by Madau et al. (1998).

In this paper we examine further the star-formation origin of gamma-ray bursts. Our approach is different from that of earlier studies in several aspects. First, we incorporate a luminosity function for GRBs. The standard-candle assumption used in previous studies is no longer tenable because the inferred peak luminosities for GRB 971214 and 970508 differ by a factor of ~ 30. Second, we use the star formation rate given by Steidel et al. (1998). This rate at $z \gtrsim 1.5$ is substantially higher than that used in the previous analyses, and therefore may change the predicted redshift distribution of GRBs. Third, we make specific predictions for the sizes and magnitudes of the host galaxies using the Hubble Deep Field data, which allow us to examine whether the model is consistent with the observations that GRB hosts are usually faint and small.

2. Model

Since most of our results are nearly independent of cosmology, we adopt an Einstein-de Sitter cosmology in our discussion. The luminosity function of gamma-ray bursts is assumed to be independent of redshift and has a power-law form

$$\phi(L)dL = \mathcal{R}_\star (L/L_\star)^\beta d(L/L_\star),\ L_{\min} \le L \le L_{\max}, \qquad (1)$$

where $L_\star$ is a characteristic luminosity (to be chosen below). (We also tried a log-normal distribution and found very similar results.) The rest-frame GRB spectra are also modelled as a power-law ($dN/dE \propto E^{-\alpha}$). This is clearly a simplification given that GRBs have diverse spectra (Band et al. 1993; Mallozzi, Pendleton & Paciesas 1996). A more realistic treatment

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involves the correction of the observed spectra (for bright GRBs) to the rest frame, because even these bright bursts may cover a substantial range in redshift (Fenimore & Bloom 1995). This has been performed for the standard-candle case by Fenimore & Bloom (1995). Unfortunately, such a treatment is more complicated for our case with a luminosity function. We therefore adopt the power-law simplification. Mallozzi et al. (1996) gave $\alpha = 1.1 \pm 0.3$; we take a slightly larger value ($\alpha = 1.5$) to partially take into account the high-energy steepening in the GRB spectra. As we will see in Sect. 3, this choice reproduces the results obtained by other authors using more realistic spectra.

The GRB rate is taken to be proportional to the star formation rate. We use the most recent star formation history determined by Steidel et al. (1998). The star formation rate at $1.2 < z < 4$ given by Steidel et al. is much higher than the estimate of Madau et al. (1998). At the moment there is no observational constraint on the star formation rate for $z > 4$. Beyond this redshift, we simply assume that the star formation rate drops by a factor of 10 per unit redshift. Since most bursts are below redshift of 4 in our model (see Fig. 1), our results are insensitive to this extrapolation.

The four model parameters, $\Delta L \equiv \log(L_{\rm min}/L_{\rm max})$, β, $L_{\rm max}$, and the rate parameter $\mathcal{R}_\star$ are found using the same procedures as in Fenimore & Bloom (1995). This method minimizes the χ^2 measure of the observed counts of GRBs, N, in 11 bins of the peak-count rate, P (in units of $\rm counts\, cm^{-2}\, s^{-1}$). $L_{\rm max}$ can also be substituted by the maximum redshift ($z_{\rm max}$) out to which a burst with luminosity $L_{\rm max}$ can still be seen. We choose $L_\star$ to be $L_{\rm max}/30$, approximately the median peak luminosity observed. Following Fenimore & Bloom, we only consider bursts with $P > 1$ on the 1024 ms time-scale from the BATSE instrument to avoid threshold effects. Our analysis applies primarily to the long bursts in the BATSE catalogue and we quote the energy in the 50-300 keV range.

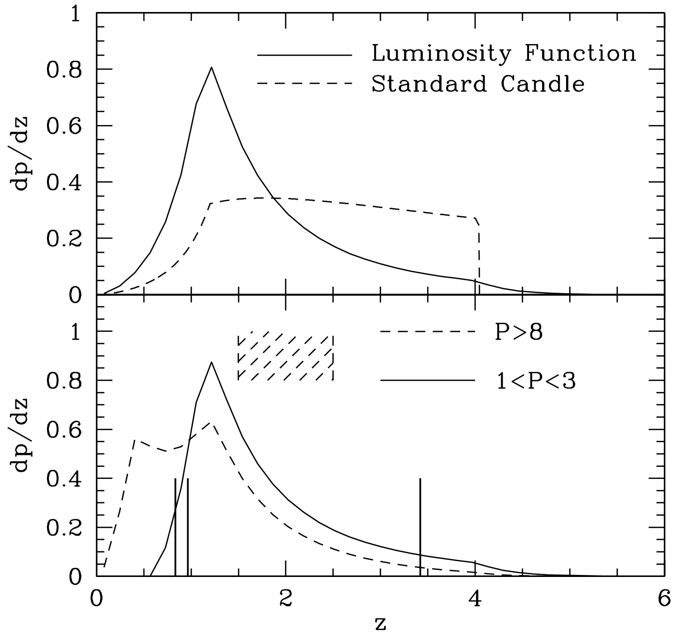

Fig. 1. The top panel shows the predicted redshift distributions for two models with the GRBs luminosity function modelled as a power-law (*solid line*) and standard candles (dashed line). Both models assume the burst rate to be proportional to the star formation rate in the universe. The bottom panel shows the redshift distribution for GRBs with $P > 8$ (*dashed*) and $1 < P < 3$ (*solid*), where P is the peak-count rate in units of $\rm counts\, cm^{-2}\, s^{-1}$. The three solid lines show the three redshifts (from left to right) for GRB 970508, 971214 and 980703 (see text). The shaded region is the likely redshift range for GRB 970228.

3. Results

We first fit the $\log N - \log P$ relation assuming a standard-candle model for GRB luminosities and a *constant* burst rate (in comoving units) in an Einstein de-Sitter universe. This model has two parameters: $L_{\rm max}$ ($z_{\rm max}$) and $\mathcal{R}_\star$. The best fit model has $z_{\rm max} = 0.73, \mathcal{R}_\star = 45 h^3 {\rm Gpc^{-3}\, yr^{-1}}$, where h is the present-day Hubble constant in units of $100\, {\rm km\, s^{-1}\, Mpc^{-1}}$. These values are in good agreement with those obtained from a more sophisticated modelling by Fenimore & Bloom (1995) and Wijers et al. (1998). The fit is excellent, with $\chi^2 = 9.1$ for 9 degrees of freedom, confirming the conclusions of previous studies that a non-evolving standard-candle GRB population provides a good fit to the $\log N - \log P$ curve. However, the standard-candle assumption is no longer supported by recent observations, as discussed in Sect. 1.

Next we fit the data with the model described in the last section. The best-fit parameters are $\beta = -2.1^{+0.3}_{-0.3}$, $\mathcal{R}_\star = 0.17^{+0.17}_{-0.1} h^3 {\rm Gpc^{-3}\, yr^{-1}}$, $\Delta L = -2.2^{+0.4}_{-\infty}$, $L_{\rm max} = 3.5^{+3.5}_{-1.6} \times 10^{52} h^{-2} {\rm erg\, s^{-1}}$, with $\chi^2 = 9.1$ for 7 degrees of freedom. The value of $L_{\rm min}$ is not constrained because very faint bursts can only be seen in a small volume and so are not well sampled for $\beta > -2.5$. The redshift distribution for GRBs is shown in the top panel of Fig. 1. As one can see, the predicted distribution peaks at $z \sim 1$, and about 15 percent of the bursts have redshifts larger than 2.5. For comparison, we show in the same panel the redshift distribution predicted by a standard-candle model and where the burst rate is proportional to the star formation rate (this model is not to be confused with the model presented at the beginning of the section where the comoving rate of GRBs is constant). With $\chi^2 = 17$ for 9 degrees of freedom, this model is not favored by the data. Note that the fraction of high-redshift hosts in the luminosity-function model is actually lower than that in the standard-candle model, because intrinsically faint bursts are numerous and can be observed only when they are nearby.

In a standard-candle model, the peak-count rate has a one-to-one correspondence with redshift. This is in contradiction with the observations that GRB 971214 and 980703 have similar peak-count rates but very different redshifts (see below). The one-to-one correspondence no longer holds when we incorporate a luminosity function for the bursts. This is illustrated in the bottom panel of Fig. 1 where we plot the predicted redshift distributions for bursts in two count-rate ranges, $1 < P < 3$ (solid) and $P > 8$ (dashed). For the standard-candle model, all bursts with $P > 8$ have $z < 1.3$ while those with $1 < P < 3$ have $z > 2.2$. The three vertical ticks indicate the redshifts of

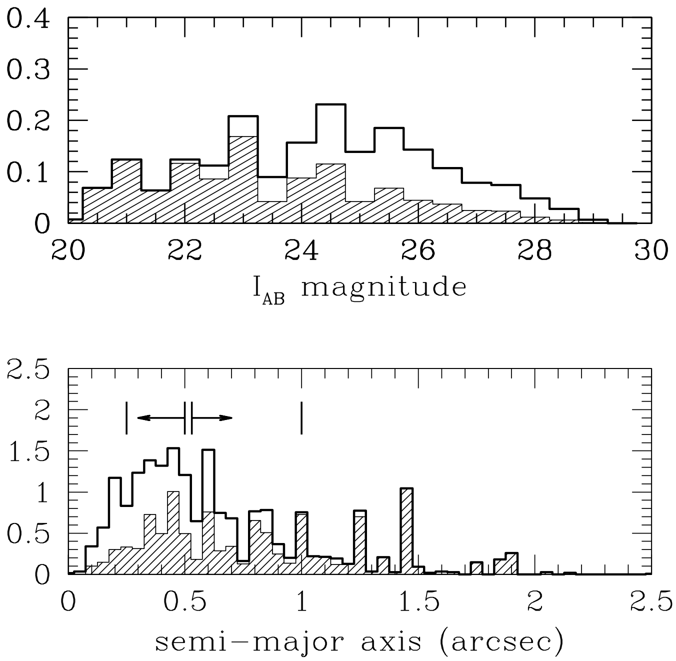

Fig. 2. The predicted magnitude (*top panel*) and semi-major axis size (*bottom panel*) distributions for host galaxies of GRBs. The shaded histograms are for GRBs with $z < 1.5$. The size or size limits for four GRB hosts are indicated (see text).

GRB 970508 ($z = 0.835$, Bloom et al. 1998), GRB 971214 ($z = 3.42$, Kulkarni et al. 1998), and GRB 980703 ($z = 0.966$, Djorgovski et al. 1998a). These bursts have $P = 0.96, 1.95, 2.4$ respectively. The shaded region indicates the probable redshift range, $1.5 \lesssim z \lesssim 2.5$ for GRB 970228 which has $P = 9$ (Van Paradijs et al. 1997). As one can see, the observed redshifts can well be accommodated in the luminosity-function model but probably not in the standard-candle model. We caution, however, that the lower cutoff in redshift for the $1 < P < 3$ bursts is sensitive to the width of the luminosity function, ΔL, which is not well constrained by the present data.

One striking feature of the observed GRB hosts is that they have very faint magnitudes and small sizes. This lack of bright GRB hosts was called the "no host" problem before the discovery of the optical counterparts (Schaefer 1998). Here we examine whether this feature can be explained in our model. To make theoretical predictions for the size and magnitudes of the host galaxies, it is necessary to know how star formation is partitioned in galaxies with different sizes and luminosities. Unfortunately, this information is not yet complete, particularly in the redshift range from 1.5 to 2.5 (where there are no optical lines for identifying redshifts). The situation will be improved in the future by the use of high-resolution infrared spectrographs. At the moment, however, one has to make assumptions based on the number counts of faint galaxies (see Hogg & Fruchter 1998) or use photometric redshifts.

In this paper, we adopt the second approach. We use the photometric redshift sample of Lanzetta et al. (1996) in the Hubble Deep Field (Williams et al. 1996) to sample the properties of the GRB host galaxies. The Lanzetta et al. sample provides the I-band magnitude (in the AB system), semi-major axis sizes and photometric redshifts for 1683 galaxies. We use the tabulated flux at 3000 Å rest (calculated from the template spectra) as an indicator for the star formation rate (Lilly et al. 1996). The photometric redshifts are reasonably accurate (Hogg et al. 1998), and are sufficient for our purpose of assigning an approximate redshift to a GRB host galaxy in a statistical sense. A Monte-Carlo approach is adopted to assign size and luminosity to a host galaxy. We first generate the redshift of a burst according to the redshift distribution shown in the top panel of Fig. 1. We then select a galaxy randomly from the galaxies in the Hubble Deep Field that are within $\delta z = 0.04$ of the redshift generated, with the probability of choosing a particular galaxy being proportional to its star formation rate. Fig. 2 shows the resulting magnitude and size distributions for the GRB hosts. The median I_{AB} magnitude is about 24.5 magnitude, with 90 percent of the galaxies lying in the range from 21.5 to 28 magnitude. This distribution is quite similar to that obtained by Hogg & Fruchter (1998) using different procedures. Seven of the nine observed GRB host galaxies have Vega-calibrated R_{AB} magnitudes between 24.5-25.7 (Hogg & Fruchter 1998), roughly corresponding to our I_{AB} of 24.0-25.2. These galaxies are therefore at the peak of the magnitude distritution. For the other two galaxies, one has $I_{AB} \sim 22$, and one has $R_{AB} > 22$. Clearly, a larger sample of GRB host galaxies is needed to see if the predicted magnitude distribution indeed matches the observed one. The expected size are quite small, with the median semi-major axis being about $0.5''$ and 90 percent of the hosts having sizes smaller than 1.3$''$. The shaded histogram shows the magnitudes and sizes of host galaxies with $z < 1.5$. Not surprisingly, these galaxies are on average brighter and have larger sizes than the hosts at $z > 1.5$. Notice that a fair fraction of galaxies at $z < 1.5$ are also faint and small. These are the faint blue galaxies which dominate the number counts and may have a substantial contribution to the star formation rate at intermediate redshifts (see Ellis 1997 for a review). For comparison, we show the sizes or size limits for four observed galaxies, GRB 970228 ($\sim 1''$, Sahu et al. 1997), GRB 970508 ($\approx 0.25''$, Fruchter et al. 1998), GRB 971214 ($\gtrsim 0.5''$, Kulkarni et al. 1998), GRB 980703 ($\lesssim 0.5''$, Djorgovski et al. 1998a). The predicted size distribution is consistent with the observations.

4. Summary and discussion

We have studied the properties of the GRB hosts in a scenario where the burst rate is proportional to the star formation rate and the effect of the burst luminosity function is taken into account. The GRB hosts have their redshift distribution peaked around $z \sim 1$, and about 15 percent have $z > 2.5$. Since the star formation rate at $z \sim 3$ is dominated by Lyman-break galaxies (Steidel et al. 1998), this high-redshift fraction of hosts should have properties similar to that of the Lyman-break galaxies. It is therefore interesting to note that the host of GRB 971214 indeed resembles a Lyman-break galaxy found at comparable redshift (Kulkarni et al. 1998). These high-redshift host galaxies likely have circular velocity larger than $250\,\mathrm{km\,s^{-1}}$ (Mo, Mao

& White 1998b), while those lower redshift hosts (in particular the faint blue galaxies) may have smaller circular velocity ($\sim 50-100\,\mathrm{km\,s^{-1}}$). The difference in the circular velocity may be relevant for distinguishing the "hypernova" model from the scenario where GRBs are produced by mergers of binary neutron stars (Bloom et al. 1998). The sizes of GRB hosts are small, 90 percent of them having sizes smaller than $1.3''$. The observed sizes match this prediction. The host galaxies are faint and have I_{AB} between 21.5 and 28. Most host galaxies are within one magnitude of the predicted most likely value. This may, however, be a selection effect: bright galaxies presumably are more metal-rich and so the GRB afterglows may suffer more dust extinction. More observations of GRB host galaxies are needed to give a stringent constraint on the model.

Although our best-fit model has a luminosity width of about two decades, most bursts occur in a narrower range. This is because the faint bursts can be observed only locally while the bright ones are not numerous. For the best fit, the median peak luminosity is $\approx L_\star = L_{\rm max}/30 \approx 10^{51} h^{-2} {\rm erg\,s^{-1}}$, while 90% of GRBs are within $L_\star/3 < L < 8L_\star$. The "effective" duration for the long GRBs is $\Delta t \approx 10{\rm s}$ (Mao, Narayan & Piran 1994), therefore the typical total energy of GRBs is $\approx L_\star \Delta t = 10^{52}$ h^{-2} erg. For a flat model with $\Omega_0 = 0.3, \Lambda_0 = 0.7$, both the peak luminosity and total energy are larger by a factor of 2.5. Note, however, that the *maximum* peak luminosity and total energy can be a factor of ~ 10 larger.

Further tests of the model come from gravitational lensing and the cosmological time dilation of GRBs. To estimate the lensing probability, we model galaxies as singular-isothermal spheres with constant comoving number density. The lensing probability is about one in two thousand, and therefore the number of lensing events in the BATSE experiment should not be significant. The predicted relative time dilation for bursts with $P > 8$ and $1 < P < 3$ is about a factor of 1.3, consistent with the lower end of the values reported by Bonnell et al. (1997). Note that such analyses make the implicit assumption that bursts at different redshifts are statistically the same, which may not be true. For example, in our model which takes into account the burst luminosity function, intrinsically faint bursts mostly occur at low redshift (cf. Fig. 1). So some caution should be exercised in interpreting results which are based on the standard candle model (e.g., Deng & Schaefer 1998). If the GRB duration is luminosity-dependent, then the interpretation of the time dilations will be more complicated. In addition, galaxies themselves evolve, for example, galaxies at high-redshift are smaller and denser (e.g. Mo, Mao & White 1998a). Such evolution might affect the predictions of GRB afterglows since they all depend on the density of the ambient medium (e.g., Waxman 1997).

Acknowledgements. We are grateful to Bohdan Paczyński for encouragement, to him, Peter Schneider and Simon White for helpful comments on the paper, to A. Fenandez-Solo for information about HST data.

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