SEVERE NEW LIMITS ON THE HOST GALAXIES OF GAMMA-RAY BURSTS

BRADLEY E. SCHAEFER
Yale University, Physics Department, JWG 463, New Haven, CT 06520-8121; schaefer@grb2.physics.yale.edu

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ABSTRACT

The nature of gamma-ray bursts (GRBs) remains a complete mystery, despite the recent breakthrough discovery of low-energy counterparts, although it is now generally believed that at least most GRBs are at cosmological distances. Virtually all proposed cosmological models require bursters to reside in ordinary galaxies. This can be tested by looking inside the smallest GRB error boxes to see if ordinary galaxies appear at the expected brightness levels. This Letter reports on an analysis of the contents of 26 of the smallest regions, many of which are from the brightest bursts. These events will have $z < 0.4$ and small uncertainties around the luminosity functions, $K$-corrections, and galaxy evolutions, whereas the recent events with optical transients are much fainter and hence have high redshifts and grave difficulties in interpretation. This analysis strongly rejects the many models with peak luminosities of $10^{57}$ photons s$^{-1}$ as deduced from the log $N$-log $P$ curve with no evolution. Indeed, the lower limit on acceptable luminosities is $6 \times 10^{58}$ photons s$^{-1}$. The only possible solution is either to place GRBs at unexpectedly large distances (with $z > 5.9$ for the faint BATSE bursts) or to require bursters to be far outside any normal host galaxy.

Subject heading: gamma rays: bursts

1. INTRODUCTION

The discovery of low-energy counterparts for gamma-ray bursts (GRBs) (Costa et al. 1997; van Paradijs et al. 1997; Frail et al. 1997; Metzger et al. 1997) has not yet solved the problem of the location of the burster sites. Measured redshifts associated with optical transients have values of $0.83 < z < 2.1$ (Metzger et al. 1997), $z = 3.42$ (Kulkarni et al. 1998), $z = 0.0085$ (Galama et al. 1998), and $z = 0.967$ (Djorgovski et al. 1998) for bursts of faint peak flux. Only in the first and last cases are the connections between the spectrum and the burst firmly resolved. The early models of cosmological bursts placed them at distances corresponding to luminosities of roughly $10^{57}$ photons s$^{-1}$ (see, e.g., Fenimore et al. 1993), while it was later realized that the luminosity could be as high as $2 \times 10^{58}$ photons s$^{-1}$ if evolutionary changes are allowed (Horváth, Mészáros, & Mészáros 1996; Totani 1997; Wijers et al. 1998). The candidate host galaxy for GRB 971214 has a very high redshift, $z = 3.42$ (Kulkarni et al. 1998), which suggests that the luminosity could be even as high as $3 \times 10^{58}$ photons s$^{-1}$. With nearby, moderate, and extreme distances all indicated, it is clear that the distance scale for cosmological bursts is not well established.

Almost all proposed burst models place GRBs inside normal galaxies (see, e.g., Nemiroff 1994). These models can be tested directly by looking inside the smallest GRB error boxes to see if any plausible host galaxy. The recent accurate optical transient positions are much smaller than the classical triangulation positions, but they suffer from the faintness of the burst and hence the faintness of the expected host, so that the old bright bursts are actually more restrictive for the presence of host galaxies. Indeed, the old bright bursts are at low redshifts, where uncertainties in cosmology and galaxy properties are minimal, while the faint bursts with optical transients are at high redshifts, where $K$-corrections, cosmology, luminosity functions, and evolution have large uncertainties. Nevertheless, the striking result from both old and new GRB positions is the stark absence of galaxies at the brightness levels commonly expected.

This basic no-host galaxy dilemma was first posed by Schaefer (1992), with improvements in analysis by Fenimore et al. (1993) and Woods & Loeb (1995). The problem is that the brightest burst regions (with the smallest areas) should typically reveal normal galaxies at around 16 mag for the usual distance scales, whereas many of these boxes are empty of galaxies to fainter than 20 mag. Here a normal galaxy is taken as one drawn randomly from the Schechter luminosity function (Binggeli, Sandage, & Tammann 1988). Band & Hartmann (1998) introduced a Bayesian analysis procedure, and they concluded that an infrared database (Larson & McLean 1997) contained no useful limits while four error boxes observed with the Hubble Space Telescope (Schaefer et al. 1997) presented a serious no-host galaxy problem.

The previous analysis was based on samples either with limits for only the brightest star or galaxy in the field (Schaefer 1992; Woods & Loeb 1995), with only four regions (Schaefer et al. 1997), or with relatively large error boxes for relatively faint bursts (Larson & McLean 1997). Schaefer et al. (1998) have accumulated a large database of observations and have placed conservative limits on the $U, B, V, R, I, J, H,$ and $K$ magnitudes of the brightest possible galaxies in each of 26 of the smallest GRB error boxes (see Table 1). This compilation solves the limitations imposed by previous samples and allows for severe new constraints on any host galaxies. The peak fluxes are for 0.25 s from 50 to 300 keV in units of photons s$^{-1}$, which was almost all provided by E. E. Fenimore (1998, private communication). The magnitudes should be treated as limits since some of the values represent detection thresholds and since the host might not be the brightest galaxy in a region. The magnitudes have been corrected for extinction in our Galaxy (Zombeck 1990; Blaes et al. 1997).

Observed galaxy number densities (Jones et al. 1991; Smail et al. 1995; Gardner, Cowie, & Wainscoat 1993) can be used to calculate the magnitude of the brightest expected foreground galaxy. In Table 2, the $V$-band limits on galaxies can be compared with the magnitudes for the brightest expected foreground galaxy ($V_{\text{max}}$), with a large expected scatter due to the randomness of the brightest galaxy and the fact that some of the measures are merely limits on the brightest galaxy. The
median of the differences is $0.28 \pm 0.35$ mag for the $V$ band and $0.07 \pm 0.21$ mag for all bands. Thus, the contents of the 26 GRB error boxes are fully consistent with chance foreground galaxies alone.

2. ANALYSIS

A detailed analysis can place limits on the absolute magnitude of any host galaxy in each region, for some assumed peak luminosity. Specifically, the observed peak flux can be combined with the assumed peak luminosity to yield a luminosity distance to the burster and to its host galaxy. This luminosity distance can then be combined with the observed limits on the host magnitude to yield a limit on the absolute magnitude for the host. For the ensemble of boxes, the limits on the absolute magnitudes can then be compared with that expected for a normal Schechter luminosity function. The assumed peak luminosity can then be varied until agreement is reached.

Two classes of distance scales have been widely considered. The first can be called the “no-evolution” scenario, where the distances are those whose luminosity corresponds to $6 \times 10^{50}$ ergs s$^{-1}$ (30-2000 keV) or $10^{57}$ photons s$^{-1}$ (50-300 keV), as derived from the log $N$-log $P$ curve (Fenimore et al. 1993; Horváth et al. 1996), energetic limits for compact objects, and time dilation (Deng & Schaefer 1998). Almost all of the published papers with specific cosmological burst models require this distance scale (see, e.g., Woosley 1993; Usov 1992; Ma & Xie 1996; Lipunov et al. 1995; Holdom & Malaney 1994; Mészáros & Rees 1993). Alternatively, an “evolutionary” distance scale might have the GRB number density following the rate of massive star formation (Totani 1997; Bagot, Zwart, & Yungelson 1998; Wijers et al. 1998), with luminosities ~20 times larger.

The luminosity distance is $D = (L/4 \pi P)^{1/2}$, with $L$ the peak luminosity and $P$ the peak flux. The limit on the host’s absolute magnitude is $M = m - 5 \log D + 5$, where $D$ is expressed in parsecs and $m$ is the limit on the apparent magnitude for any host. The standard luminosity-weighted Schechter luminosity function (Binggeli et al. 1988) is adopted with $\alpha = -1$, $M^* = -21.0$ (in the $V$ band for a Hubble constant of 65 km s$^{-1}$ Mpc$^{-1}$), and a low-luminosity cutoff at $M = -14$.

The parameter $F$ is the fraction of the galaxy luminosity function that is fainter than the observed limit. The most critical $F$ measures are for bright bursts with small boxes, since these should have bright hosts and few foreground interlopers. Since restrictions from all observed bands apply simultaneously, we select the minimum value, $F_{\text{min}}$, as providing the overall limit on the position of the galaxy within the Schechter luminosity function. This selection avoids any penalty of including a limit of poor sensitivity in some band.

We can quantitatively allow for the varying importance of large versus small boxes and faint versus bright bursts by forming a weighted average of the individual $F_{\text{min}}$ values. The weight, $W$, will be the probability that the brightest galaxy in the field is the host and not some foreground galaxy. This probability is calculated from the magnitude of the brightest expected foreground galaxy and its position in the luminosity function for the assumed burst luminosity. The $W$ value does not depend in any way on observations of the contents of the region. The uncertainty in $\langle F_{\text{min}} \rangle$ will be $(\langle F_{\text{min}} \rangle - \langle F_{\text{min}} \rangle^2)^{1/2} \Sigma W^{-1}$. The weighted average $F_{\text{min}}$ will (for an assumed peak luminosity) be a measured statistic for comparison with models. The model $F_{\text{min}}$ statistic will depend on the existence of hosts. If normal hosts are the brightest galaxy in each of the fields, then the $F_{\text{min}}$ values will be distributed uniformly from zero to one, such that the average of all 26 values should be 0.5. With random foreground galaxies, the observed limits on the individual $F_{\text{min}}$ values will be larger, so that $\langle F_{\text{min}} \rangle$ can only be greater than 0.5. Similarly, for regions where a detection thresh-
old is reported, the individual $F_{\text{min}}$ values can only increase. Thus, the existence of normal host galaxies requires $(F_{\text{min}})$ to be greater than or equal to 0.5. If hosts are not present in the error boxes, then the model $(F_{\text{min}})$ value can vary from near zero for low $L$ (such that GRBs are nearby and the lack of hosts is apparent) to near unity for high $L$ (such that GRBs are very distant and the lack of hosts is not apparent against the foreground galaxies). So any acceptable model of cosmological GRBs in hosts must adopt a luminosity such that $(F_{\text{min}})$ is $\geq 0.5$.

The analysis must incorporate the effects of the redshift on the observed brightness of the burst and of the host galaxy. $K$-corrections plus $E$-corrections for a distribution of galaxy types have been adopted from evolutionary synthetic spectral models (Rocca-Volmerange & Guideroni 1988; Pozzetti, Bruzual, & Zamorani 1996). $K$-corrections for the bursts have been calculated following equations (1), (2), and (4) in Fenimore et al. (1992). I have adopted an average spectral slope index of $-1.5$ (see Fig. 46 of Schaefer et al. 1994). The use of a power-law spectral model is acceptable since the $(F_{\text{min}})$ value is insensitive to large changes in the slope (cf. Fenimore & Bloom 1995). This procedure corrects the observed peak fluxes from 50 to 300 keV for the effect of redshift. The Hubble constant and the deceleration parameter enter the problem for the value of $M^*$ and the $E$-corrections from the luminosity distance. I have adopted $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$.

3. NO-EVOLUTION CASE

We first address the no-evolution peak luminosity of $10^{57}$ photons s$^{-1}$ ($\sim 6 \times 10^{50}$ ergs s$^{-1}$). Table 2 presents the derived redshift ($z$), the most restrictive band (MRB), $F_{\text{min}}$, and $W$ for all 26 bursts. The weighted average $(F_{\text{min}})$ is 0.141 $\pm$ 0.053.

How robust is this result? (1) The $(F_{\text{min}})$ value varies from 0.153 to 0.141 as the deceleration parameter varies from 0.1 to 0.5. As the assumed Hubble constant is varied from 50 to 80 km s$^{-1}$ Mpc$^{-1}$, the $(F_{\text{min}})$ value changes from 0.125 to 0.180. (2) The $(F_{\text{min}})$ value will increase to a half by making either the low-luminosity slope equal $-2.1$ or the $M^*$ value over 5 mag fainter. The low-luminosity cutoff is unimportant for a luminosity-weighted function. (3) If only the V-band data are considered, the $(F_{\text{min}})$ value is 0.231 $\pm$ 0.063. (4) If there were some (totally unsuspected) systematic error that brightened the limits in Table 1, any such errors would have to average 2.5 mag to get $(F_{\text{min}})$ greater than 0.5. (5) If the three 1997 bursts are arbitrarily ignored, then the $(F_{\text{min}})$ value is 0.133 $\pm$ 0.051. The inclusion of GRB 971214 into Table 1 (with $R > 25.6, P_{56e} \sim 2$ photons s$^{-1}$, and $z = 3.42$) changes the $(F_{\text{min}})$ slightly to 0.155 $\pm$ 0.055. (6) If host galaxies only occupy some fraction of the error boxes, then $(F_{\text{min}})$ will vary linearly between the host + foreground level of 0.55 and the foreground alone level of 0.19. For an observed $(F_{\text{min}})$ of 0.141 $\pm$ 0.053, the 2 $\sigma$ acceptable value can be modeled by requiring that greater than 84% of the boxes do not have hosts. (7) If no $K$-corrections for the host galaxy are used, then $(F_{\text{min}})$ = 0.136 $\pm$ 0.054. As the average GRB spectral slope index changes from 1.0 to 2.5, the $(F_{\text{min}})$ value varies over a range of amplitude 0.022. (8) The analysis never uses a burst-rate density, so the result is independent of any assumptions on the rate density evolution.

What about the possibility of a luminosity function for the bursts? The effect on the $(F_{\text{min}})$ statistic will be to average it over the assumed luminosity function. To get an expected $(F_{\text{min}})$ greater than 0.5, the majority of the bursts must greatly exceed the luminosity. So a GRB luminosity function cannot solve the basic no-host galaxy dilemma.

Let me state the no-host galaxy dilemma in five ways with increasing generality: (1) The smallest classical GRB box is for GRB 790406 with $P = 45$ photons s$^{-1}$ cm$^{-2}$, so that $z = 0.09$ for the no-evolution luminosity and an $M^*$ galaxy should appear as $B = 17.8$ mag. Yet the region is empty of galaxies.
to $B = 24.29$ mag, so that any host must be greater than 6.5 mag fainter than $M^*$. (2) The existing limits on the hosts for GRB 970228 and GRB 970508 require the hosts to be in the bottom 0.3% and the bottom 2.2%, respectively (see $F_{\text{lim}}$ values in Table 2). For such faint galaxies, the luminosity function is not well known, yet it is well known enough to realize that both hosts are improbable faint were they to be normal galaxies.

(3) For the larger sample of GRBs with $W > 0.9$, the average $F_{\text{lim}}$ values are very low, with nine of the 14 events whose hosts must be in the bottom 4% of the luminosity function.

(4) The brightest galaxy in the 26 regions has a median difference from the brightest expected foreground galaxy brightness of 0.07 ± 0.21 mag, showing that the contents of the error boxes are entirely consistent with random foreground galaxies.

(5) The $\langle F_{\text{lim}} \rangle$ value is 0.141 ± 0.053, and there is no plausible means to make it $\geq 0.5$.

4. EVOLUTIONARY CASE

What about the possibility that the peak luminosity is substantially brighter than the no-evolution value? Just such a case is expected if the GRB number density follows the rate of massive star formation (Totani 1997). The combined BATSE and PVO log N–log P curve can be made consistent with average $L$ values of up to $2 \times 10^{58}$ photons s$^{-1}$ ($\sim 10^{49}$ ergs s$^{-1}$) for a careful choice of density evolution and luminosity function (Horváth et al. 1996). An equivalent way to quantify this limit is with the redshift of the BATSE 90% efficiency threshold ($z_{0.85} = 0.85$ photons s$^{-1}$), with values ranging from 2 to 3 (Totani 1997). This luminosity from the evolutionary scenario can be tested against the limits on host galaxies.

Table 2 presents the $z$, MRB, $F_{\text{lim}}$, and $W$ for all 26 bursts on the assumption that $L = 2 \times 10^{58}$ photons s$^{-1}$ (with $z_{0.85} = 3.2$). The $\langle F_{\text{lim}} \rangle$ value is 0.291 ± 0.118 (compared with the 0.55 value expected for normal host + foreground), with most of the information coming from five bursts with small boxes. All but one of the bursts have $z$ around 0.5, so that $K$-corrections and luminosity functions are still known with some confidence. The $\langle F_{\text{lim}} \rangle$ is inconsistent with the presence of host galaxies in the GRB regions at the 2.2 $\sigma$ confidence level. The addition of GRB 971214 changes only slightly ($F_{\text{lim}}$) to 0.323 ± 0.106. For $F_{\text{lim}}$ to be greater than 0.5, $L$ must be greater than $10^{59}$ photons s$^{-1}$ (with $z_{0.85} = 7.9$), although a luminosity of $6 \times 10^{58}$ photons s$^{-1}$ (with $z_{0.85} = 5.9$) is at the 1 $\sigma$ limit. This represents a conservative limit since (1) the brightest galaxy in the box might not be the host, (2) half the relevant limits merely represent detection thresholds, and (3) the host + foreground case predicts $\langle F_{\text{lim}} \rangle = 0.55$.

Uncertainties rise as the hosts are pushed to farther distances. For example, the effects of uncertainties in the cosmological parameters increase, the role of dust in obscuring young galaxies could perhaps become important, and the luminosity function might change significantly. Fortunately, the bursts used in this study are very bright (the median for bursts with $W > 0.1$ is $P_{356} = 45$ photons cm$^{-1}$ s$^{-1}$) and hence close, and so cosmological uncertainties are small, there is no abnormal dust obscuration, and the luminosity function is substantially unchanged (Ellis et al. 1996). In contrast, the bursts with transients are systematically fainter (the median for the nine bursts is $P_{356} = 3.3$ photons cm$^{-1}$ s$^{-1}$) and hence farther away by a factor of $\sim 3$, and so they have many more problems caused by cosmology, dust, and evolution. This crucial difference is why host galaxy limits from the bright bursts are more constraining than limits from the faint bursts with small boxes.

5. POSSIBLE SOLUTIONS

There must be some solution to the no-host galaxy dilemma. I can only think of two classes of solutions, first where the bursts are placed at very large cosmological distances and second where bursters do not reside in normal hosts galaxies.

If GRBs are placed at extreme distances, then the required peak luminosity is $L > 6 \times 10^{58}$ photons s$^{-1}$, with the BATSE faint bursts at $z_{0.85} > 5.9$. Any such model would have to fine-tune the cosmology and density evolution to produce the long $\sim 3/2$ slope region of the PVO log N–log P curve (Fenimore et al. 1993). Any such model needs to explain the $z < 2.1$ limit for GRB 970508 (Metzger et al. 1997) and the $z = 0.967$ redshift for GRB 980703 (Djorgovski et al. 1998). Any such model is inconsistent (Deng & Schaefer 1998) with the observed time dilation of burst light curves (Norris et al. 1994; ‘t Zand & Fenimore 1996; Deng & Schaefer 1998). Finally, any such model places bursts at distances already rejected by limits on gravitational lensing (Marani 1998).

GRBs might not reside in normal galaxies for various reasons. It might be that bursters were ejected from their galaxy of origin at high velocity so as to now appear far away. But any ejection mechanism must be greater than 84% efficient. Also, an analysis of six high-latitude bright bursts with small boxes shows that the area around the box is empty, forcing the average ejection-to-burst time to be greater than $2 \times 10^7$ yr for ejection velocities of 500 km s$^{-1}$ for the canonical peak luminosity. A second possibility is that the hosts are of a greatly subluminous population, with a luminosity function that has $M^*$ fainter by 4.9 mag. Such an assumption would require identifying an appropriate population and explaining why normal galaxies do not produce bursts. A final alternative is that GRBs are in intergalactic space, yet then there is no known source of compact objects of the required energy.

In conclusion, gamma-ray bursters are strongly shown not to reside in normal host galaxies at either the no-evolution distance scale ($L = 10^{57}$ photons s$^{-1}$ and $z_{0.85} = 0.69$) or the evolutionary distance scale associated with bursts as tracers of star formation ($L = 2 \times 10^{58}$ photons s$^{-1}$ and $z_{0.85} = 3.2$). This no-host galaxy dilemma rejects many models and forces GRBs either to be at very large distances ($L > 6 \times 10^{58}$ photons s$^{-1}$, with the BATSE faint bursts at $z > 5.9$) or not to be in normal host galaxies.

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