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Properties of GRB Host Galaxies

Dieter H. Hartmann
Department of Physics and Astronomy, Clemson University, hdieter@clemson.edu

David L. Band
CASS, UC San Diego

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Dieter H. Hartmann[1] and David L. Band[2]

[1] *Department of Physics and Astronomy, Clemson University, Clemson, SC 29634*
[2] *CASS, UC San Diego, La Jolla, CA 92093*

Abstract. The transients following GRB970228 and GRB970508 showed that these (and probably all) GRBs are cosmological. However, the host galaxies expected to be associated with these and other bursts are largely absent, indicating that either bursts are further than expected or the host galaxies are underluminous. This apparent discrepancy does not invalidate the cosmological hypothesis, but instead host galaxy observations can test more sophisticated models.

THE ABSENCE OF THE EXPECTED HOST GALAXIES

Observations of the optical transients (OTs) from GRB970228 [19] and GRB970508 [2] have finally provided the smoking gun that bursts are cosmological. In most cosmological models bursts occur in host galaxies: are these galaxies present, and conversely, what can we learn from them? Underlying any confrontation of theory and data must be a well defined model. Here we show that the host galaxy observations are not consistent with the expectations of the simplest cosmological model, and that these observations can be used to test more sophisticated models.

In the simplest ("minimal") cosmological model the distance scale is derived from the intensity distribution logN–logP assuming bursts are standard candles which do not evolve in rate or intensity. Bursts occur in normal galaxies at a rate proportional to a galaxy's luminosity. This model predicts the host galaxy distribution for a given burst. Are the expected host galaxies present?

For GRB970228 an underlying extended object was found [19], but its redshift and nature have not been established. If the observed "fuzz" is indeed a galaxy at $z \sim {}^1\!/_4$, it is ∼5 magnitudes fainter than expected for a galaxy at this redshift. For GRB970508 no obvious underlying galaxy was observed [14] and the nearest extended objects have separations of several arcseconds, but spectroscopy with the Keck telescopes [10] led to the discovery of absorption and emission lines giving a GRB redshift of $z \geq 0.835$. The *HST* magnitude limit $R_{\rm lim} \sim 25.5$ [14] for a galaxy coincident with the transient again suggests a host galaxy fainter than expected.

Similar conclusions follow from the inspection of IPN error boxes [1,16,17], but see also [6,20]. This absence of sufficiently bright host galaxies is often called the "no-host" problem, which is a misnomer. The point simply is that if galaxies such as the Milky Way provide the hosts to most bursters, and if their redshifts are less than unity, as predicted by the minimal model, we expect to find bright galaxies inside a large fraction of the smallest IPN error boxes.

To demonstrate this quantitatively, consider the apparent magnitude of a typical host galaxy, which we assume has $M_*(B) = -20$ (approximately the absolute magnitude of an L_* galaxy—see discussion below). Using Peebles' notation [13], the apparent magnitude is

$$m = 42.38 + M + 5\,\log\left[y(z)(1+z)\right] + K(z) + E(z) + A(\Omega, z) + \chi(z) \quad , \qquad (1)$$

where $K(z)$ is the usual K-correction, $E(z)$ corrects for the possible evolution of the host galaxy's spectrum, A is the sum of Galactic foreground (position dependent) and intergalactic extinction, and $\chi(z)$ represents any corrections that apply in hierarchical galaxy formation scenarios, where galaxies are assembled through the merger of star forming subunits. The commonly found term $5\log(h)$ is already absorbed in eq. (1). Neglecting potentially large corrections from the K, E, A, and $\chi(z)$ terms, a host like the Milky Way with $M \sim -20$ would have an apparent magnitude $m \sim 22$ for redshifts of order unity. Several small IPN error boxes have no galaxy of this magnitude or brighter. Our simplified treatment agrees with Schaefer's conclusion [16,17] that typical galaxies at the calculated burst distance are absent from burst error boxes.

Thus bursts are further than predicted from the logN–logP distribution without evolution, or they occur in underluminous galaxies; an extreme limit of the latter alternative is that bursts do not occur in galaxies.

HOST GALAXIES AS A PROBE OF COSMOLOGICAL MODELS

The search for host galaxies is a powerful test of cosmological burst models. From the two above mentioned OTs we conclude that GRBs are cosmological, but the observations have not fixed the distance scale quantitatively, nor have they determined the energy source. While the x-ray, optical, and radio lightcurves (for GRB970508 only) are consistent with the predictions of the basic "fireball afterglow" picture, the fireball's central engine could be the merger of a neutron star binary, the collapse of a massive, rotating star, or the jet produced by accretion onto a massive black hole residing at the center of an otherwise normal galaxy.

The host galaxies found within burst error boxes are a powerful discriminant between different models for the burst energy source. Note that the region within which a host would be acceptable surrounding the sub-arcsecond localizations of an OT is effectively the error box for the host galaxy. Almost all models assume that bursts are associated with galaxies; the issue is the relationship between the burst and the host. In models such as the momentary activation of a dormant massive black hole the burst rate per galaxy is constant. On the other hand bursts are an endpoint of stellar evolution in most models, and therefore to first order we expect the burst rate per galaxy in these models to be proportional to the galaxy's mass and thus luminosity. These two model classes have different host galaxy luminosity functions $\psi(M)$ with different average values of M (the absolute magnitude). In the first case, $\psi(M)$ is proportional to the normal galaxy luminosity function, while in the second case $\psi(M)$ is proportional to the normal galaxy luminosity function weighted by the luminosity $L \propto 10^{-0.4M}$. We approximate the normal galaxy luminosity function with the Schechter function:

$$\Phi(M) = \kappa \; 10^{0.4(M_*-M)(\alpha+1)} \; \left[\exp\left(-10^{0.4(M_*-M)}\right)\right] \tag{2}$$

where κ is the normalization, α is the slope of the faint end, and M_* is the absolute magnitude of an L_* galaxy. Here we use $\alpha = -1$. In the B band $M_*(B) = -19.53$, which corresponds to $L_*(B) = 1.8 \times 10^{10} L_\odot \; h_{75}^{-2} \sim 3 \times 10^{11} \; L_\odot(B) \; h_{75}^{-2}$. In Figure 1 we show the cumulative distributions for the host galaxy magnitudes for the two model classes. As can be seen, the average host galaxy magnitude (i.e., at 0.5) differs by ~ 1.75 magnitudes.

However, we can make better predictions about the host galaxies in cosmological models where bursts are a stellar endpoint. In such models, the burst rate should be a function of the star formation rate (SFR). If there is a substantial delay (e.g., of order a billion years or more) between the GRB event and the star forming activity that created the progenitor, then the burst rate integrates over a galaxy's SFR, and we would not expect the host galaxy to display the signatures of recent star formation. Furthermore, if the progenitor is given a large velocity, then it may travel a large distance from the host galaxy before bursting, and it may become impossible to associate a galaxy with the burst.

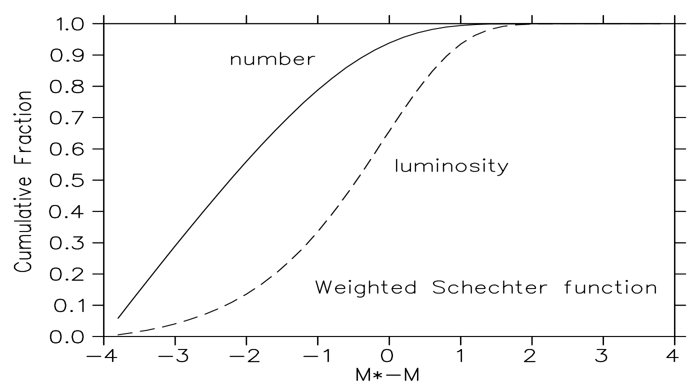

FIGURE 1. The cumulative distribution of host galaxy magnitudes if their luminosity function is weighted by number or luminosity. If GRBs trace light, the 50% point is near M_*. If it is proportional to galaxy number a typical host would be ~ 2 magnitudes fainter.

In many models the burst occurs shortly after its progenitor star forms (e.g., within a hundred million years or less). We would then expect that on average bursts would occur in galaxies showing evidence of recent star formation. The burst rate should be proportional to the SFR, both for individual galaxies and for a given cosmological epoch.

In particular, the burst rate and the SFR should have the same history, as was recently considered by several groups [12,15,18,21]. Extensive redshift surveys and data from the Hubble Deep Field have reliably determined the cosmic star formation history to $z \sim 5$ [3,4,7–9]. The data clearly suggest a rapid increase in the comoving SFR density with increasing redshift, SFR $\propto (1+z)^4$, reaching a peak rate (at $z \sim 1.5$) about 10–20 times higher than the present-day rate, and decreasing slowly to the present value by $z \sim 5$. This evolution function, $\eta(z)$, enters the differential rate vs. (bolometric) peak flux

$$\partial_P R \propto P^{-5/2}\ \mathrm{E}(z)^{-1}\ \eta(z)\ (1+z)^{-3}\ \left[(1+z)\partial_z y(z) + y(z)\right]^{-1} \quad , \qquad (3)$$

where $\mathrm{E}(z)$ and $y(z)$ are defined in [13]. For small redshifts the logarithmic slope of this function is Euclidean, i.e. $-5/2$. The solid curve of Figure 2 shows the effects of geometry (bending of logN–logP) and the dashed curve demonstrates how $\eta(z)$ compensates for the geometry out to the redshift at which the cosmic SFR peaks. At larger redshifts the effects of geometry and decreasing SFR then combine and the slope flattens quickly. Comparison with BATSE data suggests that this SFR model deviates from the pseudo-Euclidean slope too abruptly. While several studies [15,18,21] report that the observed SFR generates a brightness distribution consistent with BATSE data, our findings support the different result of Petrosian & Lloyd [12], who suggest that other evolutionary effects must be present in addition to the density evolution described by $\eta(z)$. While a good fit to the data requires

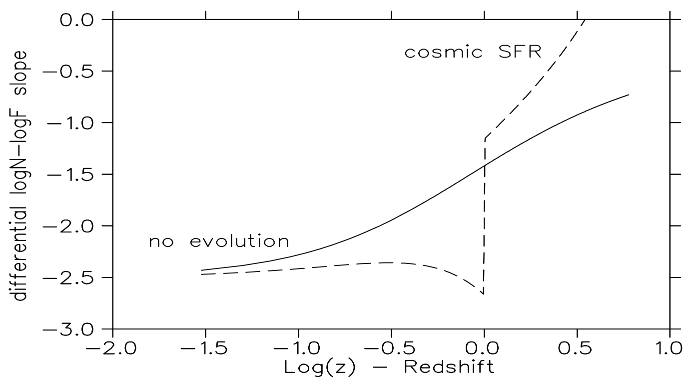

FIGURE 2. The slope of the differential GRB brightness distribution. Non-evolving sources (solid curve) quickly show significant deviation from the Euclidean value $-5/2$ with increasing redshift. If the GRB rate is proportional to the SFR (see text) the apparent Euclidean slope extends to $z \sim 1$ (dashed curve). For greater z the geometry of the universe together with a now decreasing burst rate cause the slope to deviate rapidly from $-5/2$.

a more sophisticated model of source evolution, the basic message is likely to be the same: the logN–logP distribution does not exclude GRB redshifts much greater than unity.

Therefore, the absence of the host galaxies predicted by the "minimal" cosmological model does not call the cosmological origin of bursts into question. Instead, host galaxy observations will teach us where bursts occur.

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