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Host galaxy statistics

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Abstract. The galaxies observed within the error boxes of gamma-ray bursts are inconsistent with the host galaxies predicted by the simplest "minimal" cosmological model where bursts emit $\sim 6\ 10^{50}$ ergs but are consistent with a standard candle energy of $\sim 10^{53}$ ergs (if radiated isotropically). Although these calculations utilize the host galaxy data but not the burst intensities, we have developed the methodology to use all the available observations to model the redshift and intensity distributions.

Key words: gamma-rays: bursts — methods: statistical

There are three inter-related scientific questions about gamma-ray bursts: 1. Where do bursts occur – at what redshifts and in which environments? 2. What is the mechanism by which the energy is released (e.g., binary mergers, collapsars)? 3. How do they radiate (i.e., internal vs. external shocks, synchrotron emission)? Many aspects of these fundamental questions can be addressed by determining empirically the burst redshift and intrinsic intensity distributions (in this work we use the total burst energy as the fundamental burst intensity). The redshift distribution traces the evolution of the progenitor population and thus will suggest its nature (e.g., a burst rate proportional to the universe's star formation history might favor collapsars); the redshifts will establish the energy required of the burst source. The energy distribution will determine which energy sources are feasible and may indicate whether there are multiple source populations (e.g., if the distribution is multimodal).

Unfortunately, the current burst observations do not provide a direct distance indicator, such as spectral lines at known energies, which in conjunction with the total energy fluences can give the bursts' energies and distances. Therefore, we have to rely on indirect observables. The redshift of absorption lines of an associated optical transient or of spectral lines from the presumed host galaxy underlying the burst's afterglow is the closest to a direct distance measure. Since the observed burst intensity – here the energy fluence – decreases with distance, it is an indirect distance measure. Finally, the observed brightness of the host galaxy also indicates the burst distance; this is the focus of our work.

These observables are interpretable in the context of models about bursts and their characteristics. A model may be as simple as the assumption that the redshift of the burst and the apparent host galaxy are the same, or may be a parameterization of the distribution of a burst property. Thus we need models for the redshift distribution, the burst energy distribution, and the host galaxy brightness. For example, we assume that the host galaxies are normal galaxies and that the burst rate is proportional to the galaxy luminosity. Assuming that bursts are standard candles is a model of the energy distribution.

In our research program we apply statistical techniques to the available observations of the burst ensemble to determine the redshift and energy distributions. We estimate the parameters of assumed model distributions and test specific models. As always, we are wary of selection effects which will bias our results; in many cases the potential selection effects are model-dependent (e.g., by assuming observables are or are not correlated).

Our first exercise was resolving the "no host galaxy" issue. The question as originally posed (Schaefer 1992) was whether the host galaxy observations are consistent with the "minimal cosmological model". This model assumes that: bursts are standard candles with no density or luminosity evolution; the burst energy can be determined from modeling the fluence distribution; and bursts occur in galaxies at a rate proportional to the galaxy luminosity (Fenimore et al. 1993). Schaefer (1992) noted that the relatively small error boxes for bright bursts did not contain galaxies of the brightness expected under the minimal model; however, this claim was contested (Larson 1997). We developed a Bayesian odds ratio which compares the hypothesis that the host galaxy predicted by our

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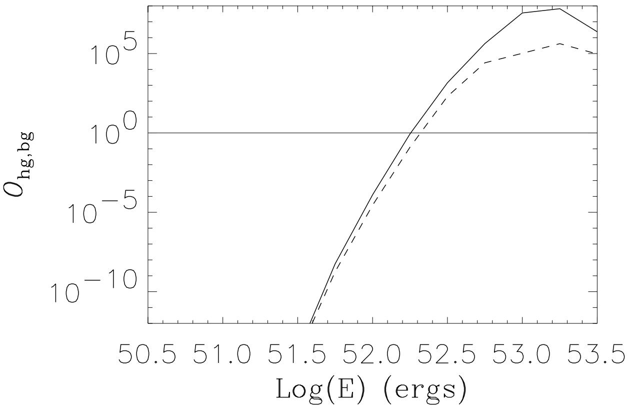

Fig. 1. Odds ratio as a function of the total burst energy (assumed radiated isotropically) for $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.1$. The observations consist of 23 finite-sized error boxes and 8 galaxies associated with optical transients

cosmological model is present in a burst error box to the hypothesis that only unrelated background galaxies are present (Band & Hartmann 1998). The odds ratio is the sum of the probability that the host galaxy is fainter than our galaxy detection limit and the probabilities that each observed galaxy is the host galaxy as opposed to an unrelated galaxy. Built into this methodology is a treatment of the size of the error box. Our odds ratio of $\sim 2\ 10^{-6}$ indicates that the galaxies in the error boxes are too faint to be the host galaxies predicted by the minimal model.

Next we asked what burst energy is consistent with the host galaxy observations (Band et al. 1999). For this calculation we used both the host galaxies associated with the recent optical transients and the upper limits from the finite-sized error boxes of less well-localized bursts (few arcmin^2). Note that even extremely well determined optical transients have "error boxes" of a few arcsec^2 within which a galaxy would be acceptable as the host. Once again we assumed a burst is a standard candle which occurs at a rate proportional to the host galaxy's luminosity. We calculated the odds ratio we derived for the "no host galaxy" issue and varied the burst energy; thus we do not require consistency of the redshift distribution with the observed fluence distribution. Because the burst energy, and therefore the redshift, are now much larger than predicted by the minimal cosmological model, we have to apply color and evolution corrections to the galaxy observations. Figure 1 shows that the odds ratio peaks for $E \sim 10^{53}$ erg (assumed to be radiated isotropically).

Are selection effects a problem in this analysis? Probably not. Since standard candle bursts all have the same energy, the burst trigger is not biased towards more or less energetic bursts. Our method accounts for galaxies below the limiting magnitude, and further, host galaxies have been detected for all the optical transients observed thus far. A possible selection effect is that the brightness of the optical transient may be correlated with the galaxy type; for example, optical transients may be brighter (and more easily detected) in denser environments. Indeed, optical transients have been detected in only $\sim 2/3$ of the bursts localized by *Beppo-SAX*.

These studies were originally motivated by the debate over whether there was a "no host galaxy" problem, and therefore evaluated the consistency of the host galaxy observations with the assumed burst model. A more systematic approach which uses all the observations to determine the redshift and burst energy distributions is warranted. We advocate constructing a likelihood function for models given all the available data; the overall likelihood function is the product of likelihoods for each burst given the data available for that burst. Of course the probabilities used in the likelihoods must account for the detection thresholds. Simulations show the resulting likelihoods are correct if the thresholds are understood.

For the forseeable future there are three cases. First, in the ideal case both the redshift and the fluence are known, and consequently the burst distance and its energy are determined directly. In this case the host galaxy information is unnecessary for determining the redshift and energy, but can be used to test the host galaxy model (e.g., whether the hosts are normal galaxies). Sufficient bursts are required to constrain the distributions.

Second, as is the case for most bursts in the PVO and BATSE databases, only the fluences are determined. The fluence distribution is the convolution of the redshift and energy distributions, therefore providing a powerful constraint on these distributions when analyzed in conjunction with bursts with more data.

Finally, there are bursts for which the fluences and magnitudes of the apparent underlying host galaxies are measured. For this group the host galaxy brightness constrains the burst redshift to a range, given a model for the host galaxies. While determining the redshift exactly would be optimum, the host galaxy magnitude does provide usable distance information in addition to the burst fluence, allowing us to extract the maximum information from the observations.

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