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Present and Future Prospects for GRB Standard Candles

A.S. Friedman(1), and J.S. Bloom(1),(2)

(1) *Harvard Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.*
(2) *Dept. of Astronomy, 601 Campbell Hall, Univ. of California, Berkeley, Berkeley, CA 94720.*

Summary. — Following our previous work, we conclude that a GRB standard candle constructed from the Ghirlanda et al. power-law relation between the geometry-corrected energy (E_γ) and the peak of the rest-frame prompt burst spectrum (E_p) is not yet cosmographically useful, despite holding some potential advantages over SNe Ia. This is due largely to the small sample of $\sim$ 20 GRBs with the required measured redshifts, jet-breaks, and peak energies, and to the strong sensitivity of the goodness-of-fit of the power-law to input assumptions. The most important such finding concerns the sensitivity to the generally unknown density (and density profile), of the circumburst medium. Although the E_p–E_γ relation is a highly significant correlation over many cosmologies, until the sample expands to include many low-z events, it will be most sensitive to Ω_M but essentially insensitive to Ω_Λ and w, with some hope of constraining dw/dt with high-z GRB data alone. The relation clearly represents a significant improvement in the search for an empirical GRB standard candle, but is further hindered by an unknown physical basis for the relation, the lack of a low-z training set to calibrate the relation in a cosmology-independent way, and several major potential systematic uncertainties and selection effects. Until these concerns are addressed, a larger sample is acquired, and attempts are made to marginalize or perform Monte Carlo simulations over the unknown density distribution, we urge caution concerning claims of the utility of GRBs for cosmography and especially the attempts to combine GRBs with SNe Ia.

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1. – Motivations for a GRB Standard Candle

It has long been recognized [1, 2, 3], that standard candles constructed from long duration Gamma-ray bursts (GRBs) would have several potential advantages over Type Ia Supernovae (SNe Ia), the most important being high redshift detection. Whereas detected SNe Ia are currently spectrally classifiable out to a maximum of $z \sim 1.7$ with

HST [4] (and in the future with *SNAP* [5]), $\sim$ 25% of GRBs with known z (10 of 39) already have measured redshifts > 2. Although there are diminishing returns for observations at higher redshifts — which primarily probe the matter-dominated regime — such measurements may be of great interest if the dark energy shows exotic time variation. In practice, $\sim$ 50% (9 of 19) GRBs in the current sample of bursts with measured redshifts (z), jet break times ($t_{\rm jet}$), and peak energies (E_p), are in the redshift range $0.9 < z < 2$, which is *already* comparable to the number of high-z SNe Ia discovered with *HST* [6]. This regime is clearly important for constraining Ω_Λ, w, its possible time variation, and the transition redshift to the epoch of deceleration [6, 7]. In addition to high-z detection, γ–rays penetrate dust, GRB spectra [8] are simpler than SNe Ia spectra, yielding potentially cleaner k-corrections [9], and with massive star progenitors [10], any long GRB evolution would likely be orthogonal to that of SNe Ia, ensuring different systematics. GRB standard candles could thus provide a useful independent check to cosmography with SNe Ia.

2. – Present Status of the E_p–E_γ Relation: Sensitivity to Input Assumptions

Previous attempts to constrain cosmological parameters with GRB energetics [1, 2, 3, 11] were thwarted by what are now known as wide distributions in the isotropic equivalent energies ($E_{\rm iso}$) and beaming-corrected energies (E_γ), which span more than ~ 4 and ~ 2 orders of magnitude, respectively [12]. In particular, the once-promising E_γ distribution [13, 11], widened with the discovery of new low energy bursts (e.g. 030329). Expanding upon the well known E_p–$E_{\rm iso}$ "Amati" relation [15], Ghirlanda *et al.* recognized that many under-energetic bursts appeared softer in the rest-frame prompt γ–ray spectrum than those with higher E_γ, discovering the remarkable E_p–E_γ "Ghirlanda" relation [14], which can be cast as a power-law $E_p \propto (E_\gamma)^\eta$. In [12], we confirm this correlation (Fig. 1a herein), and demonstrate that although the goodness of fit to a power-law is strongly sensitive to input assumptions (particularly the circumburst density), the relation itself is still highly significant over a range of plausible cosmologies. As recently suggested [16, 17, 12], the relation could be used to create a standardized GRB candle with an empirical correction to the energetics similar to the light-curve shape corrections used to standardize the peak magnitudes of SNe Ia [18]. However, without knowing the slope of the power law *a priori* from physics or from a low-z training set, in the cosmographic context, it is imperative to re-fit for the slope of the power law from the data for each cosmology [17, 12] (Fig. 1a inset), lest circularity problems arise (e.g. [16]). Even so, greater obstacles to cosmography with current data involve small number statistics and the sensitivity of the goodness of fit of the relation to input assumptions [12].

Unlike peak magnitudes of SNe Ia light curves, computing E_γ (see eq's 1, 2 of [12]) depends on **(a)** the cosmology, **(b)** a model assumption for the energy structure of the jet, **(c)** the effective rest-frame "bolometric" bandpass for the GRB k-correction [9], and **(d)** parameters which are often unknown for most bursts; namely the ambient ISM density n (possibly a stellar wind profile [19]), and the γ–ray creation efficiency (ξ), where the same values of n, ξ are assumed for all GRBs when unknown. Assuming $n = 10 \pm 5$ cm^{-3}, $\xi = 0.2$ (20%), for our sample of 19 GRBs, we find a goodness of fit of $\chi^2_\nu = \chi^2/\mathrm{dof} = 3.71$ (17 dof) for the $[20, 2000]$ keV bandpass [12]. At this conference, Ghirlanda et al. first reported $\chi^2_\nu = 1.27$ (13 dof) for their sample of 15 GRBs [20]. In [12], we demonstrate that the discrepancy in χ^2_ν arises mainly from different references for individual bursts (*i.e.* small number statistics), and from slightly different input assumptions for n, σ_n, illustrated here in Fig. 1b. Poor fits to the relation result in unacceptable fits in the

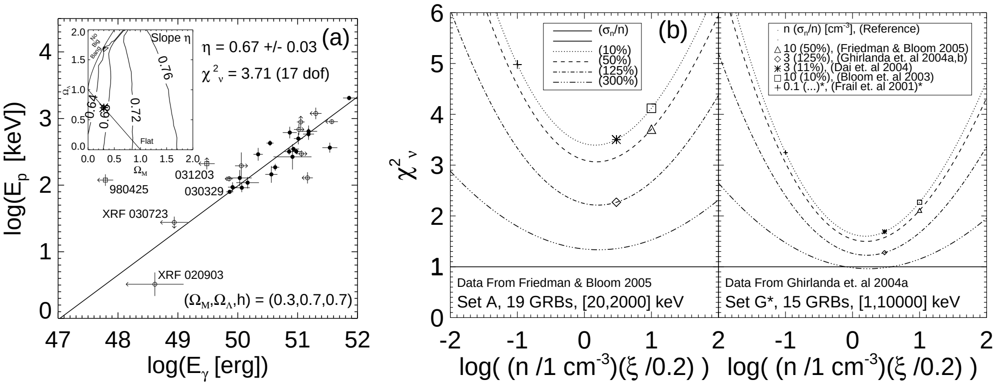

Fig. 1. – **(a)** E_p–E_γ relation, plotted from Tables 1,2 of [12], with only 19 GRBs used in the fit (filled circles). Upper/lower limits (open circles) are denoted with arrows. Inset shows weak cosmology dependence of slope η. **(b)** Sensitivity of χ^2_ν to assumptions for density n (error σ_n). Data, are from [12]: left, [14]: right. Curves are for $\sigma_n/n = [0.1, 0.5, 1.25, 3.00]$ from top down. Plot symbols show assumptions from previous work. Independent of data set, k-cor bandpass, $n \sim 1$–2 cm $^{-3}$ minimizes χ^2_ν. Derived χ^2_ν are left: 3.71 (17 dof), big triangle; right: 1.27 (13 dof), small diamond. In decreasing importance, discrepancy comes from data references, density assumptions, sample size, k-cor bandpass. **(a)** and **(b)** assume $\xi = 0.2$, $(\Omega_M,\Omega_\Lambda,h)$=(0.7,0.3,0.7).

GRB Hubble diagram, rendering the χ^2 contours over $(\Omega_M,\Omega_\Lambda)$ meaningless; however, this sensitivity also allows most outlier bursts in Fig. 1a to be made consistent with the relation by changing the density (or its error) to otherwise reasonable values [12].

Using the relation for cosmography, in [16], although the authors claim tight constraints on the matter density (assuming flatness), they fail to self-consistently re-fit the slope of the relation for each cosmology and exclude several outlier bursts (e.g. 990510, 030226) on grounds not adequately justified. Recently, those authors have improved upon these points in follow-up work [22]. In [17], the authors re-fit the relation self-consistently, but did not stress the cosmographic power of GRBs alone, instead performing a joint fit with SNe Ia, claiming that the joint fit is more consistent with flatness than SNe Ia alone. However, the analysis in [17] understresses the fact that GRBs alone appear to favor a loitering cosmology [12] (although see [21]). Despite improvements, the most recent follow up work [21, 22] does not address the sensitivity to input assumptions [12]. However, by performing simulations of future data [22], and developing new statistical techniques [21], the recent work had indicated some potentially exciting new directions for GRB cosmology.

3. – Future Prospects

Although a major step forward, a GRB standard candle constructed from the E_p–E_γ relation can not yield meaningful constraints on the cosmological parameters for the current data, mainly due to the small sample (with very few low-z events) and to the strong sensitivity of the goodness of fit of the relation to density assumptions. Selection effects [23, 24] and other potential systematics [12] must also be addressed before using GRBs for precision cosmography. However, *Swift* should detect > 200 GRBs over the next ~ 2 years [25]. Of these, redshift constraints are expected for a majority of the bursts, either from the on-board broad-band spectroscopy or ground-based follow-up spectra. With early-time light curves from the *Swift* UVOT instrument and a fleet of dozens of ground-based follow-up programs, $t_{\rm jet}$ could be measured for a substantial fraction of these bursts. Unfortunately, future E_p measurements may be hindered by the relatively narrow spectral range of *Swift* ([15,150] keV), further strengthening the science case for the ongoing symbiosis with *HETE II*, due to its larger [30,400] keV bandpass.

Even for a sample including an order of magnitude more GRBs with measured z, $t_{\rm jet}$, and E_p, we believe that density constraints will remain the limiting factor for cosmography, since each requires detailed broadband afterglow modeling (e.g. [26]). This is independent of a low-z training set or a theoretical prediction that constrains the slope of the relation *a priori*. Future work will then require using the known information about the *distribution* of densities to marginalize over or sample statistically from such a distribution with Monte Carlo simulations [12]. While the current data do not uniquely support a good fit for the relation to a power law, they certainly do not rule out one. As such, it is still possible that GRB standard candles from this relation might place meaningful constraints on the cosmological parameters, most notably the time variation of the dark energy.

However, even if the relation is never able to seriously constrain cosmology, with the beaming-corrected energy E_γ, it is more physically motivated than the Amati relation [15] (also see [23, 24]), it may lend insight into GRB radiation physics [14, 27, 28], and could help us to identify new classes of GRBs (*i.e.* different progenitors) [12]. Independent of its ultimate fate as a potential GRB standard candle, the discovery of the E_p–E_γ Ghirlanda relation [14] clearly represents an exciting new direction for the GRB field.

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