NASA GSRP Proposal: Testing the Cosmological Applications of Long-Duration Gamma-Ray Bursts with the NASA/GSFC *Swift* Satellite

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1. Introduction

Long duration GRBs, cosmological events linked to the deaths of Massive Stars and Type Ib/c supernovae, are among the brightest explosions in the universe. Although GRBs are most certainly not standard candles in terms of their isotropic equivalent γ-ray energy $E_{\rm iso}$ or their beaming-corrected γ-ray energy E_γ (Frail et al. 2001; Bloom et al. 2003), recently discovered empirical correlations, most notably involving the spectra and energetics of GRBs, indicate that GRBs may be *standardizable* candles, representing a new class of cosmological distance indicators complementary to SNe Ia (Ghirlanda et al. 2004a,b; Friedman & Bloom 2005b,a; Liang & Zhang 2005; Xu 2005).

Much excitement surrounding GRB cosmology has ensued following the launch of the highly successful NASA/Goddard Space Flight Center *Swift* satellite, a dedicated space mission to study GRBs (Gehrels et al. 2004). In concert with a coordinated worldwide network of ground-based follow up programs linked in real time to *Swift* GRB localizations, individual *Swift* bursts have already been detected up to $z = 6.29$ (GRB 050904; Kawai et al. 2005) and may even be detectable out to redshifts as high as $z \sim 20$ (Lamb & Reichart 2000; Bromm & Loeb 2002). In contrast, $z \sim 1.7$ is the effective upper limit for detection *and* reliable spectral classification of Type Ia vs. Type II/Ib/Ic SNe with NASA's *Hubble Space Telescope* (; e.g. SN1997ff; Riess et al. 2001), and proposed future space based experiments like SNAP, JEDI, and DESTINY, (Aldering et al. 2004; Crotts et al. 2005; Lauer 2005) candidates for the NASA/DOE Joint Dark Energy Mission (JDEM). On the other hand, with currently flying space satellites like NASA's *Swift*, *HETE-II* and ESA's *Integral*, GRBs could help extend the Hubble diagram to unprecedented redshifts, doubling the current GRB spectra/energetics sample from ~ 20 to ~ 40 GRBs just within the next few years.

As such, the proposed project aims to **quantify the extent to which GRBs can be used as reliable standardizable candles to measure the cosmological parameters and constrain the expansion history of the universe.** Of particular interest is the question of how much light GRB standardized candles could shed on constraining the dark energy responsible for the current acceleration of the universe and its potential variation over cosmic time

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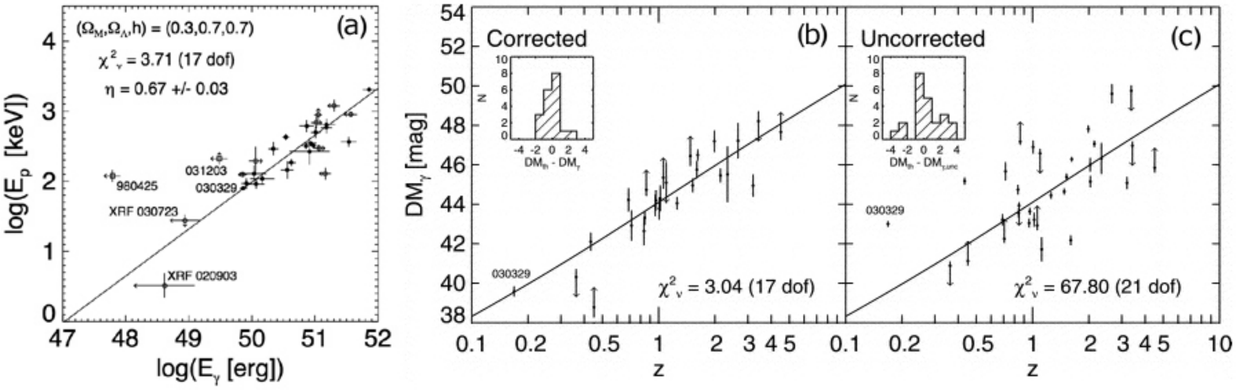

Fig. 1.— The E_p–E_γ relation, a recent step toward a standardized candle using GRB energetics and spectra (adapted from Friedman & Bloom 2005a). The improvement in the GRB Hubble diagram with (b) and without (c) the empirical E_p–E_γ correction. All plots assume a $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $H_o = 70$ km s^{-1} Mpc $^{-1}$ cosmology.

(Riess et al. 2004a). Following our previous work, this project will investigate both the potential applications and possible systematic errors which could undermine the cosmological utility of GRBs (Friedman & Bloom 2005b,a). The most important data for this project would come from the NASA/GSFC *Swift* satellite, making the work directly relevant to the science goals of the NASA GSRP research opportunity at GSFC.

2. Advantages and Complementary Applications of GRB Cosmology

In addition to their high-z detection and practical use years before the next generation supernova space experiments, GRB standardized candles offer several other potential advantages compared to SNe Ia. Since γ-rays penetrate dust, a GRB standardized candle could avoid potential systematic errors inherent in SNe due to dust extinction. Furthermore, since most bright GRB γ–ray spectra are well described by a simple, smooth broken power law, (the "Band" model; Band et al. 1993; Preece et al. 2000), cosmological k-corrections for GRBs (Bloom et al. 2001) are, in principle, more tractable than traditional optical K-corrections for SNe (Friedman & Bloom 2005b).

With Type Ia SNe thought to be thermonuclear detonations of White Dwarf stars near $1.4 M_\odot$ (Hillebrandt 2004), and GRBs likely due to the collapse of massive, rapidly rotating Wolf-Rayet stars (Woosley 1993; MacFadyen et al. 2001), both samples necessarily contend with unknown evolution of the progenitor systems (see § 3). However, because of very different physics in the emission mechanisms, any such evolution of the standard candle would unlikely be the same for GRBs and SNe Ia, at least allowing for independent checks of such systematic errors.

The different redshift distributions of GRBs (peaking at $z \gtrsim 2$; Natarajan et al. 2005) and SNe Ia (peaking at $z \gtrsim 1$; Barris & Tonry 2006) allow for complementary probes of the cosmological parameters, with GRBs most sensitive to the matter density (Ω_M) and SNe Ia sensitive essentially to the difference between the matter and dark energy densities ($\Omega_M - \Omega_\Lambda$). At first glance, then, it is not obvious that the $z > 1.7$ region is useful for studying dark energy, since it is in the matter dominated epoch (Friedman & Bloom 2005b; Mörtsell & Sollerman 2005). However, Linder & Huterer (2003) argue that accurate measurements of the dark energy equation of state parameter w or its time variation w_a require a full survey at least in the range $0 < z < 2$ to deal with systematics and degeneracies only resolvable at high-z (See their figures 3–5). In addition, a robust measurement of Ω_M from GRBs would strongly complement previous constraints on Ω_M from Large Scale Structure (LSS) measurements (e.g. 2dF: Percival et al. 2001, or SDSS: Tegmark et al. 2004). In the future, *best* prior on Ω_M may come from GRBs, and since a good prior on Ω_M is crucial for constraining w with SNe Ia (Mörtsell & Sollerman 2005), a combination of GRBs and SNe Ia could be fundamental to the global scientific study of dark energy.

With a lack of a nearby calibration sample (see § 3), constraining w or w_a with GRBs appears unlikely (Mörtsell & Sollerman 2005). However, the current best examples of GRB standardized candles give distance estimates with statistical errors of $\sim$ 20%–25% (0.4–0.5 mag; Friedman & Bloom 2005b; Xu et al. 2005) as opposed to only $\sim$ 7%–9% (0.15–0.2 mag) for SNe Ia (Riess et al. 2004b). If future *Swift* data reveal new correlations with significantly smaller scatter, the prospects for GRBs constraining dark energy may become much more promising (e.g. Hooper & Dodelson 2005). In particular, since $\sim$ 90% of localized Swift long GRBs have detected X-ray afterglows (Burrows & Swift XRT Team 2005), improved spectra-energetics correlations may be discovered using X-ray afterglow data from the *Swift* XRT instrument.

3. Potential Drawbacks of GRB Cosmology

The current GRB energetics/spectra relations with the smallest scatter include the E_γ–E_p relation (Ghirlanda et al. 2004a; Fig. 1 herein), and the similar, but purely empirical E_p–$E_{\rm iso}$–$t_{\rm jet}$ relation (Liang & Zhang 2005; Xu 2005). Both relations minimally require measurements of several GRB observables including the spectroscopic redshift (z), the peak-energy of the rest frame prompt γ-ray spectrum (E_p), and the time of the jet-break in the optical/X-ray/radio afterglow ($t_{\rm jet}$). As such, they have only been fit from a small sample of $\sim$ 20 GRBs with the relevant measurements, still in the regime of small number statistics.

Other proposed GRB standardized candle relations exist in the literature, including those involving the temporal and spectral properties of the γ-ray light curves alone (e.g., variability; Fenimore & Ramirez-Ruiz 2000; Reichart et al. 2001; Lloyd-Ronning & Ramirez-Ruiz 2002; Schaefer 2003) and/or spectral evolution (e.g., spectral lags; Norris et al. 2000; Schaefer et al. 2001; Norris 2002). While these have larger scatter, they are based on properties of the prompt γ-ray emission alone. As such, more GRBs have the required measurements since they do not require expensive follow up observations of the GRB afterglow, although all methods require a spectroscopic redshift. However the method for incorporating these relations into the GRB Hubble Diagram fit is still under debate (Friedman & Bloom 2005b; Firmani et al. 2005; Xu et al. 2005; Mörtsell & Sollerman 2005; Schaefer 2005). Some researchers (e.g. Schaefer 2005) have attempted to use all methods simultaneously, and although this allows as many as 52 GRBs to be placed on the Hubble Diagram, it obscures the potential systematics for each method and is not obviously better than simply using the single relation with the smallest scatter and the best understood systematics.

All methods suffer from potential systematic errors including calibration issues, selection effects, and uncertain physical mechanisms. These included difficulties with low-z calibration due to a lack of a nearby training set of GRBs, possible outlier contamination by distinct sub-classes of GRBs, and sensitivity to model assumptions (Friedman & Bloom 2005b). Of considerable concern is the question of GRB luminosity evolution with redshift favored both theoretically (Woosley 2005) and empirically (Kocevski & Liang 2006). Since this type of evolution could mimic the effects of time varying dark energy ($w_a \neq 0$), it represents a possible systematic error which could fundamentally limit measurements of w or w_a.

4. Research Experience

My undergraduate research at UC Berkeley with Professor Alex Filippenko involved generating optical light curves of Type Ia SNe found using the Lick Observatory Supernova Search (Li et al. 2000). For my first graduate research project at Harvard, I worked with Professor Joshua Bloom and Professor Ramesh Narayan to explore the potential for turning GRBs into standardized candles for cosmology (Friedman & Bloom 2005b,a; Friedman et al. 2004; Friedman & Bloom 2004). My thesis advisor in the Harvard Astronomy Department is professor Robert Kirshner, a leader in the field of supernova cosmology, dark energy, and the acceleration of the expansion of the universe (e.g. Kirshner 2003). My proposed thesis project, which also includes work on SNe Ia in the near infrared (Friedman et al. 2005) should be completed within the next 2–3 years, and would be aided considerably with a NASA GSRP fellowship.

5. Resources at GSFC

The proposed NASA Technical Advisor at GSFC is Dr. Neil Gehrels, the Principal Investigator of the *Swift* satellite, whom I have been in correspondence with regarding this project. Since the project would rely heavily on current and future *Swift* data, such a collaboration with Dr. Gehrels and the *Swift* team is ideal, since they understand the details of data that go beyond what can be found in the literature. In particular, the leading GRB standardized candles require measurements of the peak energy of the prompt γ–ray spectrum (E_p), and the narrow $[15, 150]$ keV bandpass of the *Swift* BAT instrument limits this measurement. However, the BAT detects fluence out to ~ 350 keV, which raises the possibility of placing limits on E_p which may otherwise go unreported. This is something that would require specific discussions with *Swift* team members familiar with the response function of the instrument. Also of interest is the search for new spectra/energetics relations with the large set of XRT afterglow data, an investigation which would be greatly enhanced by input *Swift* from scientists on the XRT instrument team. Overall, such an insider perspective may be crucial towards undertaking a careful analysis of GRB cosmology.

6. Conclusion

The recent, well motivated excitement regarding GRB cosmology has not been without some controversy. As it stands, there is still considerable, and perhaps overstated, emphasis on using GRBs to probe the dark energy and its potential time variation (e.g. Ghirlanda et al. 2004b; Lamb et al. 2005; Schaefer 2005), and a major aim of this project is to help clarify what can and can not be done with GRB standardized candles, now and in the future. For this $\sim$ 2–3 year project, we will continue to compile a database of new GRBs that can be placed on the Hubble Diagram ($\sim$ 5–10 / yr.), investigate various distance estimators, analyze potential systematic errors, and develop optimal methods for extracting cosmological parameters. While GRBs are clearly still in their infancy as standardizable candles, GRB cosmology is a promising new field which may help constrain the cosmological parameters with an independent method complementary to the concordance of Type Ia SNe, LSS, and CMB measurements. In conclusion, we hope we have presented a case for a project that is resonant with the goals of NASA GSRP opportunity at GSFC, and we thank you for considering this proposal.

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