NASA GSRP Research Proposal: Cosmological Applications of Novel Standardized Candles

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1. Introduction

Distance measurements anchor the many techniques of modern precision cosmology. Standard Candles, the idealized distance indicators consisting of astronomical sources with identical intrinsic luminosities, do not exist in nature. Nature, however, has provided several *standardizable* candles, where measurements of the apparent brightness or fluence and other observables can be combined to create a standardized distance indicator. Notable examples include the period-luminosity relation for Cepheid Variable stars (Bono & Cignoni 2005) and several methods exploiting the peak brightness-decline rate relations for optical light curves of Type Ia supernovae (SNe Ia; e.g Phillips 1993; Riess et al. 1996; Perlmutter et al. 1997; Jha et al. 2005). Most recently, empirical correlations between the spectra and energetics of long duration Gamma-Ray Bursts (GRBs; Ghirlanda et al. 2004a,b; Friedman & Bloom 2005b) and peak magnitudes of SNe Ia in the near-infrared (IR SNe Ia; Krisciunas et al. 2004; Krisciunas 2005) have appeared as promising new distance indicators.

The proposed NASA GSRP project aims to **investigate the cosmological applications of both GRBs and IR SNe Ia as new classes of standardizable candles**. We summarize current status of GRBs and IR SNe Ia in sections § 2 and § 3, respectively, outlining specific data driven projects of direct relevance to the Structure and Evolution of the Universe (SEU) opportunity through the NASA Science Mission Directorate, office of Space Sciences (SMD - SS).

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2. Cosmology with Gamma-Ray Bursts

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

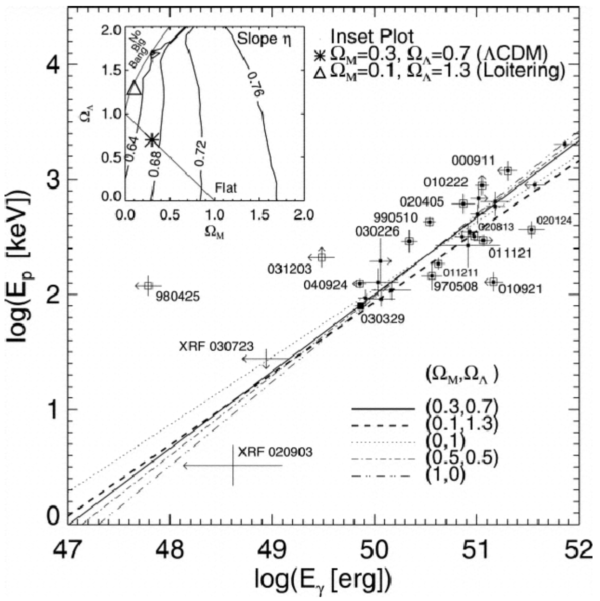

Fig. 1.— The E_p–E_γ relation, a recent step toward a standardized candle using GRB energetics and spectra (adapted from Friedman & Bloom 2005a)

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.

GRBs 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. 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 ($\Omega_M - \Omega_\Lambda$). 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.

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 ~ 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 such an approach 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.

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.

3. Cosmology With Infrared Light Curves of Type Ia SNe

SNe Ia in the near-IR may be superior distance indicators than in the optical bands. As a result, unlike optical Type Ia SNe, which are *standardizable candles* at the $\sim$ 0.18 mag level (MLCS2k2 method; Jha et al. 2005), IR SNe Ia appear to be essentially *standard candles* at the $\sim$ 0.15–0.2 mag level or better ($\sim$ 7–9% in distance), depending on the filter (Krisciunas et al. 2004; Krisciunas 2005). Compared to optical UBVRI observations, JHK light curves of SNe Ia suffer from less systematic uncertainty due to dust extinction, and show no apparent decline rate relations in the near-IR with the current, small, sample of $<$ 20 JHK SNe Ia (Krisciunas et al. 2004; Krisciunas 2005; Figure 2). If future data confirms this, IR SNe Ia may prove ideal for cosmology.

We hope to obtain a set of low redshift IR SNe data through the CfA Supernova Program using the fully robotic Peters Automated Infrared Imaging Telescope (PAIRITEL, http://www.pairitel.org, P.I. Joshua Bloom, UC Berkeley). PAIRITEL will be able to dedicate 1-2 hours a night following up $\sim$ 10–15 SNe Ia per year ($\sim$ 20–25 total nearby supernovae). With nightly cadence, this allows for densely sampled light curves ranging from as early as $\sim$ 15 days before maximum to $\sim$ 30 days past the peak, with realistic goals of $\sim$ 10% photometry overall with $\sim$ 3% accuracy near the peak (Bloom 2003; Kirshner 2005). Since its commissioning in October 2004, PAIRITEL data now include $\sim$ 15 well sampled SNe Ia in JHK. Combining this with the next 2–3 years of data should yield a sample of $\sim$ 40 well observed SNe Ia from which to construct JHK light curves, representing a homogeneous, high quality nearby training set to calibrate the Type Ia Hubble Diagram in the near-IR.

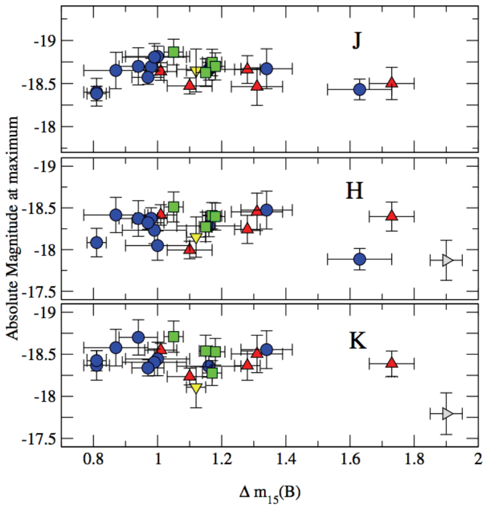

Fig. 2.— Absolute magnitudes of Type Ia SNe at maximum light vs. the decline rate parameter Δm15(B) (Fig. 2 of Krisciunas 2005). The lack of decline rate relations and intrinsic scatter of ∼ 0.15–0.2 mag make JHK SNe Ia promising cosmological distance indicators.

If nearby JHK SNe Ia prove to be excellent standard candles, it may further motivate dedicated space missions optimized for using high-z IR SNe Ia for cosmology. The basic suggestions from this work would be to extend the wavelength coverage of such satellites out to at least 2–6 μm, so that SNe Ia at $z \sim 1-2$, will have their rest-frame JHK light ($\sim$ 1.2–2.2 μm) redshifted into the satellite's bandpass. For example, the SNAP and *DESTINY* satellites (Aldering et al. 2004; Lauer 2005), candidates for the JDEM mission, are both is designed to go out to 1.7 μm. This work would motivate these teams to reconsider going out further into the IR, similar to the *JEDI* proposal, which would observe out to 4.2 μm (Crotts et al. 2005).

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 including both GRB cosmology and the new work on IR SNe Ia (Friedman et al. 2005) should be completed within the next 2–3 years, and would be aided considerably with a NASA GSRP fellowship.

5. Relevance to NASA Themes

In summary, the proposed project aims to test whether GRBs and IR SNe Ia can be used as 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 both of these new standardized candles could shed on constraining the dark energy responsible for the current acceleration of the universe and its potential variation over cosmic time (Riess et al. 2004). The project would rely on current and future data from several space satellites including NASA's *HETE-II* and ESA's *Integral* experiments, with the most important GRB data coming from the NASA/GSFC *Swift* satellite. The IR SNe Ia project would have direct bearing on future NASA mission concepts along the lines of the proposed NASA/DOE JDEM mission. As a multifaceted cosmology project, this work is of direct relevance to the NASA themes outlined in the Structure and Evolution of the Universe opportunity through the NASA Science Mission Directorate, office of Space Sciences, and we thank you for considering this proposal.

REFERENCES

Aldering, L. et al. 2004, astro-ph/0405232, PASP, submitted

Barris, B. J., & Tonry, J. L. 2006, ApJ, 637, 427

Bloom, J. 2003, 1

Bloom, J. S., Frail, D. A., & Kulkarni, S. R. 2003, ApJ, 594, 674

Bono, G., & Cignoni, M. 2005, in ESA SP-576: The Three-Dimensional Universe with Gaia, 659–+

Bromm, V., & Loeb, A. 2002, ApJ, 575, 111

Crotts, A. et al. 2005, ArXiv Astrophysics e-prints

Fenimore, E., & Ramirez-Ruiz, E. 2000, astro-ph/0004176

Firmani, C. et al. 2005, MNRAS, L32+

Frail, D. A. et al. 2001, ApJ, 562, L55

Friedman, A. S., & Bloom, J. S. 2004, 4th Workshop on Gamma-Ray Bursts in the Afterglow Era, Rome, Italy, October 18-22

—. 2005a, Il Nuovo Cimento C, 028, 669

—. 2005b, ApJ, 627, 1

Friedman, A. S., Bloom, J. S., & cosmicbooms. net. 2004, BAAS, 205,

Friedman, A. S. et al. 2005, BAAS, 207,

Gehrels, N. et al. 2004, ApJ, 611, 1005

Ghirlanda, G., Ghisellini, G., & Lazzati, D. 2004a, ApJ, 616, 331

Ghirlanda, G. et al. 2004b, ApJ, 613, L13

Jha, S., Riess, A., & Kirshner, R. 2005, ApJ submitted

Kawai, N. et al. 2005, GCN Circular 3937

Kirshner, R. 2005, A White Paper for the Dark Energy Task Force, 1

Kirshner, R. P. 2003, Science, 300, 1914

Kocevski, D., & Liang, E. 2006, ArXiv Astrophysics e-prints

Krisciunas, K. 2005, in ASP Conf. Ser. 339: Observing Dark Energy, 75–+

Krisciunas, K., Phillips, M. M., & Suntzeff, N. B. 2004, ApJ, 602, L81

Lamb, D. Q., & Reichart, D. E. 2000, ApJ, 536, 1

Lauer, T. R. 2005, New Astronomy Review, 49, 354

Li, W. D. et al. 2000, in American Institute of Physics Conference Series, 103–106

Liang, E., & Zhang, B. 2005, ArXiv Astrophysics e-prints

Lloyd-Ronning, N. M., & Ramirez-Ruiz, E. 2002, ApJ, 576, 101

Mörtsell, E., & Sollerman, J. 2005, J. Cosmology Astropart. Phys., 6, 9

Natarajan, P. et al. 2005, MNRAS, 364, L8

Norris, J. P. 2002, ApJ, 579, 386

Norris, J. P., Marani, G. F., & Bonnell, J. T. 2000, ApJ, 534, 248

Percival, W. J. et al. 2001, MNRAS, 327, 1297

Perlmutter, S. et al. 1997, ApJ, 483, 565

Phillips, M. M. 1993, ApJ, 413, L105

Reichart, D. E. et al. 2001, ApJ, 552, 57

Riess, A. G. et al. 2001, ApJ, 560, 49

Riess, A. G., Press, W. H., & Kirshner, R. P. 1996, ApJ, 473, 88

Riess, A. G. et al. 2004, ApJ, 607, 665

Schaefer, B. E. 2003, ApJ, 583, L67

—. 2005, BAAS, 207,

Schaefer, B. E., Deng, M., & Band, D. L. 2001, ApJ, 563, L123

Tegmark, M. et al. 2004, Phys. Rev. D, 69, 103501

Woosley, S. E. 2005, BAAS, 207,

Xu, D. 2005, ArXiv Astrophysics e-prints

Xu, D., Dai, Z. G., & Liang, E. W. 2005, astro-ph/0501458

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