Correlations for cosmology from the homogenization of GRB-associated supernova observations

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Resumen / Las explosiones de rayos gamma (GRBs) de larga duración han sido encontradas en asociación a supernovas (SNs) desde el emblemático caso de GRB 980425/SN 1998bw. Un GRB puede ser detectado hasta $z \sim 9$ y sus SNs hasta $z \approx 1$. Correlaciones entre sus observables podrían ser útiles, por ejemplo para estimar luminosidades intrínsecas, si no fuese por la gran diversidad en sus observaciones. A partir de una muestra de > 30 SNs asociadas a GRBs, seleccioné aquéllas con observaciones en al menos dos filtros. Desarrollé un método para calcular el brillo intrínseco de la SN de manera más exacta. Usando parámetros del GRB y de la SN misma, evalué diferentes correlaciones. Encontré que usar la energía espectral máxima del GRB y el ancho de la curva de luz de la SN resulta prometedor para estandarizar la luminosidad de las GRB–SNs. Demostré que con las GRB-SNs se pueden determinar distancias con una precisión de ∼11 %–15 %. Estos resultados ofrecen nuevas oportunidades para explotar las GRB–SNs con el fin de sondear la expansión del Universo.

Abstract / Long γ-ray bursts (GRBs) have been found in association with supernovae (SNe) since the emblematic case of the GRB 980425/SN 1998bw. The GRB emission can be detected up to $z \sim 9$ and their SN counterpart has been observed up to $z \approx 1$. Correlations between GRB–SN observables could be useful, e.g. in determining extragalactic distances and intrinsic luminosities, if it was not for the large diversity of GRB–SN observations. With a sample of > 30 GRB-associated SNe from the literature, I selected those having observations in at least two filters. I developed a novel methodology to derive an accurate rest-frame SN brightness. Using parameters of the GRB emission and the SN itself, I evaluated different correlations. I found that using the GRB peak spectral energy and the SN light-curve width proves promising to standardize the SN luminosity. I demonstrated that GRB–SNe can determine distances with ∼11 %–15 % precision. These results unfold new opportunities to exploit GRB–SNe to probe the cosmic expansion of the Universe.

Keywords / supernovae: general — gamma-ray bursts: general — cosmology: observations

1. Introduction

The core collapse of some rapidly-rotating massive stars ($\gtrsim 15\,\mathrm{M}_\odot$; Smartt 2009) leads to the formation of a relativistic jet that produces a γ-ray burst (GRB). The central engine powering the jet through accretion is either a black hole or a neutron star. Then a broad-lined type Ic SN follows expelling the remainder envelope at high velocities. These GRB-associated SN are more energetic than normal type Ic SNe peaking at about $M_V = -20$ mag and expanding as fast as $40\,000\,\mathrm{km\,s^{-1}}$ (Klose et al. 2019). GRB-SNe are detected up to $z \sim 1$, therefore there has been a growing interest at turning them into distance indicators Cano, 2014; Cano et al., 2014. Moreover, future all-sky surveys, e.g. LSST, will find hundreds of orphan GRB afterglows. Thus it is necessary to develop a robust methodology to standardize the luminosity of the associated SNe. So far, studies have included only handful of events in sample analyses. Here, I present an analysis on 20 GRB-SN events, I describe the first steps towards a reliable homogenization method to attenuate the diversity of GRB-SN observations, and I show the results of evaluating correlations using rest-frame GRB and SN parameters.

2. Data & Method

The GRB and SN data were acquired from several literature sources*. The GRB data consisted of z-corrected E_{peak} measurements, while the SN data included the maximum brightness and light-curve (LC) width. The GRB quantity corresponds to an average E_{peak} over the whole duration of the γ-ray emission. The SN quantities were characterized following the approach by Zeh et al. (2004), where k and s are the luminosity ratio and stretch factor with respect to SN 1998bw. From a complete sample of > 30 events, I selected a sub-sample of 20 events for which SN observations are available in

*Galama et al. (1998); Nakamura et al. (2001); Patat et al. (2001); Christensen et al. (2004); Mazzali et al. (2003, 2006); Sakamoto et al. (2005); Watson et al. (2004); Sazonov et al. (2004); Ulanov et al. (2005); Kann et al. (2006, 2019); Ferrero et al. (2006); Campana et al. (2006); Kaneko et al. (2007); Vreeswijk et al. (2008); Golenetskii et al. (2008); Richardson (2009); Nomoto et al. (2010); Tanvir et al. (2010); Thöne et al. (2011); Starling et al. (2011); Fan et al. (2011); Cano et al. (2011, 2014); Schady et al. (2012); Melandri et al. (2012); Olivares E. et al. (2012, 2015); Gendre et al. (2013); Cucchiara & Perley (2013); Schulze et al. (2013, 2014); Klose et al. (2013, 2019); and a few more circulars.

at least two filters. Estimations of $A_{V,\mathrm{host}}$ were usually obtained from the GRB afterglow SED (e.g. Olivares E. et al. 2015) and have been taken into account to compute the final k_λ values, where λ is the filter central wavelength in the rest frame.

When plotting the k_λ-SEDs in the top panel of Fig. 1, the considerable diversity in spectral shape is immediately evident. This is mainly attributed to the different photosphere temperatures at peak luminosity. The method to apply K corrections consisted in using the relative SEDs to compute new k values for a given band at rest-frame wavelengths. This band was chosen to maximize the number of events with SED coverage. Flux differences in the spectral lines compared to SN 1998bw affecting k_λ interpolation are considered negligible in a narrow λ band, therefore a low-order polynomial interpolation of the relative SEDs was sufficient. The rest-frame λ band in which the SED coverage overlaps for different GRB-SNe is shown in grey in the bottom panel of Fig. 1. To avoid extrapolation, the narrower blue and green λ bands are defined covering $(\lambda_{1\mathrm{b}}, \lambda_{2\mathrm{b}}) = (427, 467)\,\mathrm{nm}$ and $(\lambda_{1\mathrm{g}}, \lambda_{2\mathrm{g}}) = (495, 559)\,\mathrm{nm}$, respectively. Thus, rest-frame k values are defined as $k_{\mathrm{blue}} = (1/\Delta\lambda_{\mathrm{blue}}) \int_{\lambda_{1\mathrm{b}}}^{\lambda_{2\mathrm{b}}} k_{\mathrm{i}}(\lambda)\, d\lambda$ and $k_{\mathrm{green}} = (1/\Delta\lambda_{\mathrm{green}}) \int_{\lambda_{1\mathrm{g}}}^{\lambda_{2\mathrm{g}}} k_{\mathrm{i}}(\lambda)\, d\lambda$, where $\Delta\lambda_{\mathrm{blue}} = \lambda_{2\mathrm{b}} - \lambda_{1\mathrm{b}}$, $\Delta\lambda_{\mathrm{green}} = \lambda_{2\mathrm{g}} - \lambda_{1\mathrm{g}}$, and $k_{\mathrm{i}}(\lambda)$ is the interpolation function between the available k_λ values. Analogously, I defined the rest-frame stretch factors s_{blue} and s_{green}. Uncertainties have been computed through MC simulations for k and s values in both bands.

3. Results

With custom rest-frame k and s values at hand, I explored the parameter space. The SN 1998bw data have been excluded from the analysis because of: (1) its low-luminosity GRB; (2) its massive host galaxy; (3) the undetected GRB afterglow, which prevented an accurate extinction estimation; (4) its small luminosity uncertainty, which hampers a reliable calculation of correlation dispersions. Although SN 1998bw was nearby and often used as a template, its outlier nature has extensively discussed (e.g. Woosley & Bloom, 2006).

3.1. Luminosity vs. Stretch

Initially explored by Zeh et al. (2004), the k-s plane is derived solely from SN LCs. Although when investigating the k-s plane in the blue band I found no significant correlation, for the green band (Fig. 2) I recovered a trend similar to what has been previously reported by Cano (2014). A different analysis of the k values yields an almost identical trend (solid line in Fig. 2; Klose et al. 2019). The correlation analysis for the 14 events in the green band resulted in a reduced k dispersion of $\sigma_k = 0.29$ (originally $\sigma_k = 0.37$).

3.2. SN Luminosity vs. GRB E_{peak}

This parameter plane was initially explored by Li (2008) using three GRB-SNe and the X-ray flash (XRF) SN

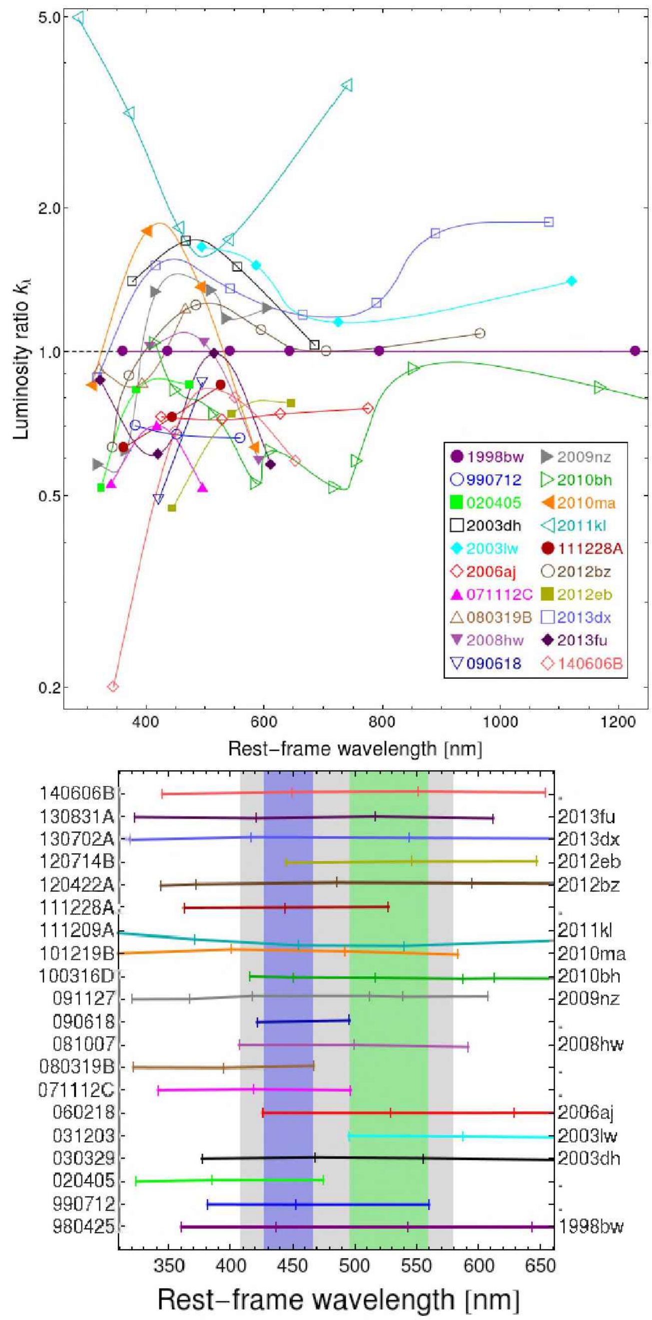

Figure 1: *(Top)* GRB-SN SEDs relative to SN 1998bw in the rest frame. Each event is represented by a different color and symbol. *(Bottom)* Vertically-separated relative SEDs of our GRB-SN sample. The blue and green regions are the λ bands that avoid extrapolation for 17 and 15 events, respectively.

2008D. Since we are aiming at homogenizing and reducing diversity, in this research I treated XRFs as a different kind of event compared to GRB-SNe and left XRF-SNe out of the sample. Again, when investigating this plane for k_{blue} I found a scatter plot. However, the correlation analysis of the 9 events in the green band resulted in a reduced k dispersion of $\sigma_k = 0.22$ (originally $\sigma_k = 0.36$) as shown in Fig. 3. The relation previously reported by Li (2008) was recovered doubling the sample size of GRB–SNe and leaving out XRF–SNe.

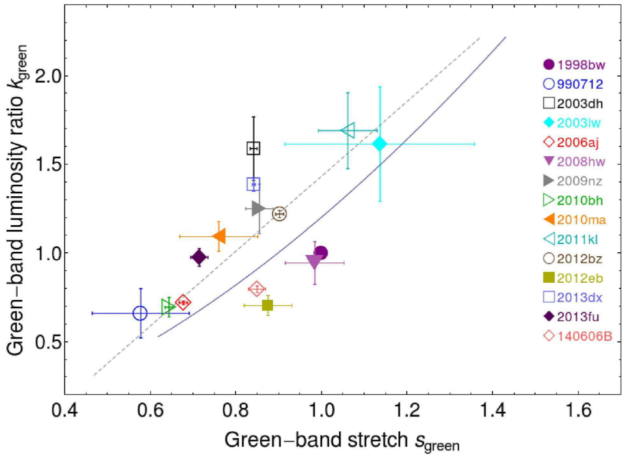

Figure 2: Luminosity ratios vs. stretch factors in the green band for 15 events. The dashed line is a weighted linear regression. The solid line corresponds to the power-law fit from Klose et al. (2019).

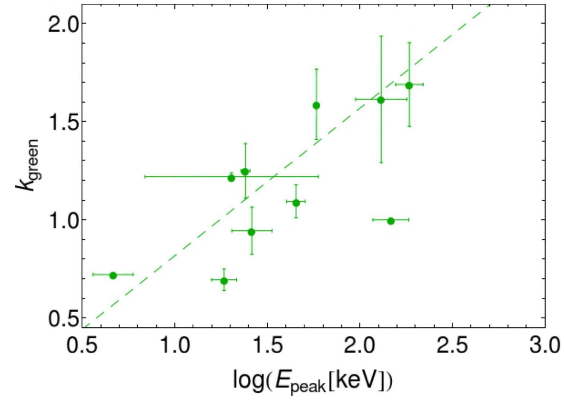

Figure 3: Peak spectral energy vs. luminosity ratios in the green band for 10 events. The dashed line is a weighted linear regression.

4. Discussion & Conclusions

So far the largest sample of >30 GRB–SNe was analyzed in search for correlations. A subset of 20 events complied with the requirements of the methodology (see §2. for details). I computed rest-frame luminosity ratios k and stretch factors s for the SN sample. The relation between luminosity and stretch is recovered with a dispersion of $\sigma_k = 0.29$, which translates into a precision in distance of 15 %.

The GRB $E_{\rm peak}$ from the γ-ray spectrum integrated over the whole event duration was corrected for the redshift of each event. It is worth noticing that estimating a characteristic $E_{\rm peak}$ for GRBs is not trivial. The average $E_{\rm peak}$ depends on the duration and variability of the γ-ray emission. Plus, there are also biases involving the estimation of $E_{\rm peak}$ from the time-integrated γ-ray spectrum and the used instrumentation. Regardless, using 9 GRB–SNe I recover the relation between the SN luminosity and $E_{\rm peak}$ previously investigated by Li (2008) with 4 events without having to include any XRF–SNe. The luminosity dispersion of $\sigma_k = 0.22$ translates into a distance dispersion of just 11 %.

When using blue-band SN parameters no significant relations were found probably due to the larger sampled by the blue band, the inclusion of peculiar events such as GRB 090618, and the diversity induced by metal absorption lines at bluer wavelength.

Although the additional dispersion in the Hubble diagram due to z was not taken into account, it is worth to highlight the reduced dispersion achieved by both investigated correlations. While the dispersion in the k-s green-band plane was reduced by 22 %, the dispersion in the k-$E_{\rm peak}$ green-band plane was reduced by 39 %, making GRB-associated SNe in promising distance indicators up to redshifts of about 0.7. It is worthy to mention that the sample size will have to be increased to allow for better statistical constraints.

Acknowledgements: Support was provided by the Ministry of Economy, Development, and Tourism's Millennium Science Initiative through grant IC120009, awarded to The Millennium Institute of Astrophysics, MAS, and FONDECYT grant 11170953.

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