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Does the Amati Relation depend on the Luminosity of the GRB's Host Galaxy? *

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Abstract In order to test the systematics of the Amati relation, 24 long-duration GRBs with available $E_{\gamma,\rm iso}$ and $E_{\rm p}$ are separated into two subgroups according to the B-band luminosity of their host galaxies. The Amati relations in the two subgroups are found to be in agreement with each other within the uncertainties. Taking into account of the well established luminosity - metallicity relation of galaxies, no strong evolution of the Amati relation with the GRB's environmental metallicity is implied in this study.

Key words: gamma-rays: bursts — gamma-rays: observations — galaxies: evolution

1 INTRODUCTION

Several relations between observable properties have been found for Gamma Ray Bursts (GRBs) in past few years (see Schaefer 2007 for a review). Among these, an important one is the Amati relation which is a correlation between the total isotropic-equivalent radiated energy in γ-ray ($E_{\gamma,\rm iso}$) of long-duration GRBs (LGRBs) and the peak energy ($E_{\rm p}$) of integrated νF_ν spectrum in the rest frame (Amati et al. 2002). This correlation is further confirmed and extended by subsequent observations (e.g., Amati 2003, 2006a,b; Sakamoto et al. 2004; Lamb et al. 2004). A similar relation between $L_{\rm iso}$ and $E_{\rm p}$ is found to hold not only among different LGRBs but also among individual pulses of a given LGRB (Liang et al. 2004). Although the correlation is highly significant, it has been shown that the dispersion of the correlation might not be entirely due to statistical fluctuation (e.g., Amati 2006a).

At present, LGRBs are generally believed to originate from the death of young massive stars (e.g., see Woosley & Bloom 2006 for a recent review). The popular collapsar model favors progenitors with low metallicity that preserve angular momentum when the collapse occurs (e.g., Woosley 1993; MacFadyen & Woosley 1999). A low metallicity environment has been revealed by studies of the host galaxies of both nearby and cosmologically distant LGRBs (e.g., Sollerman et al. 2005; Stanek et al. 2006; Fynbo et al. 2006). Because metal abundance plays an important role in the collapsar model, the evolution of the statistical properties of LGRB can be a key issue.

Li (2007) recently examined the cosmological evolution of the Amati relation by dividing 48 LGRBs with reported $E_{\rm iso}$ and $E_{\rm p}$ into four redshift bins. The Amati relation was found to vary with the redshift with only a $\sim$4% of chance of the variation being caused by selection effect. Although it is generally believed that metallicity statistically evolves strongly with the redshift, a number of extremely metal-poor galaxies have been identified in the local universe (e.g., Kewley et al. 2007; Izotov et al. 2006 and references therein). Since the metallicity is hard to determine for a large sample of LGRBs at present, the luminosity (or stellar mass) of host galaxy could be used as a physically meaningful indicator of metallicity, taking into account the well established luminosity (or mass)-metallicity relationship (L-Z relation, e.g., Tremonti

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et al. 2004; Savaglio et al. 2005). In this paper, we concentrate on examining the variation of the Amati relation with the luminosity of the LGRB's host galaxy.

2 VARIATION OF AMATI RELATION ON THE LUMINOSITY OF HOST GALAXY

We first compile a sample of LGRBs to check whether or not the Amati relation varies with the luminosity of the host galaxy. The B-band luminosities of host galaxies are adopted from the literature, and is transformed to absolute B-band magnitude by adopting $M_{\rm B}^{\star} = -21$ mag. In order to avoid selection effect, only those LGRBs with $0.2 < z < 2$ were considered. This resulted in four nearby bursts, GRB 980425, GRB 030329, GRB 031203 and GRB 060218, that were excluded from our sample. GRB 980425 is a sub-energetic LGRB and was not found to satisfy the Amati relation. GRB 031203 has poorly determined $E_{\rm p}$. The final sample contains 24 LGRBs, listed in Amati (2006a). Table 1 lists their properties, including the redshift, rest-frame isotropic energy $E_{\gamma,\rm iso}$ defined in 1–1000 keV band, peak energy $E_{\rm p}$ in the rest-frame, and k-corrected absolute B-band magnitude $M_{\rm B}$ of the host galaxy. The ΛCDM cosmology, with $\Omega_{\rm m} = 0.3$, $\Omega_\Lambda = 0.7$ and $h_0 = 0.7$, were adopted throughout the paper.

Table 1 The Sample of 24 LGRBs Used in this Work

GRB (1)	z (2)	$E_{\gamma,\rm iso}$ (erg s^{-1}) (3)	$E_{\rm p}$ (keV) (4)	$M_{\rm B}$ (mag) (5)	$t_{\rm j}$ (day) (6)	n (cm^{-3}) (7)	Ref (8)
970228	0.695	1.86 ± 0.14	195 ± 64	–17.85	....	....	1,2
970508	0.835	0.71 ± 0.15	145 ± 43	–17.85	....	....	1,2
970828	0.98	34 ± 4	586 ± 117	–18.85	2.2	2.04	1,2,7
980613	1.096	0.68 ± 0.11	194 ± 89	–19.85	....	....	1,2
980703	0.966	8.3 ± 0.8	503 ± 64	–20.90	3.4	4.18	1,2,7
990123	1.60	266 ± 43	1724 ± 466	–20.40	2.04	3.43	1,2,8
990506	1.30	109 ± 11	677 ± 156	–19.75	....	....	1,2
990510	1.619	20 ± 3	423 ± 42	–17.20	1.6	2.50	1,2,7
990705	0.842	21 ± 3	459 ± 139	–21.65	1.0	1.01	1,2,7
990712	0.434	0.78 ± 0.15	93 ± 15	–19.35	1.6	1.21	1,2,7
991208	0.706	25.9 ± 2.1	313 ± 31	–18.30	....	....	1,2
991216	1.02	78 ± 8	648 ± 134	–18.15	1.2	1.94	1,2,7
000210	0.846	17.3 ± 1.9	753 ± 26	–19.50	....	....	1,2
000418	1.12	10.6 ± 2.0	284 ± 21	–19.90	....	....	1,2
000911	1.06	78 ± 16	1856 ± 371	–18.80	....	....	1,2
010921	0.45	1.10 ± 0.11	129 ± 26	–19.75	....	....	1,2
011121	0.36	9.9 ± 2.2	793 ± 533	–16.15	....	....	1,2
020405	0.69	12.8 ± 1.5	612 ± 122	–21.50	1.67	29.49	1,2,7
020813	1.25	76 ± 19	590 ± 151	–19.30	0.43	2.04	1,2,7
020903	0.25	0.0028 ± 0.0007	3.37 ± 1.79	–19.2	....	....	1,3
030328	1.52	43.0 ± 4.0	328 ± 55	–20.4	0.8	0.58	1,4,7
030528	0.782	2.0 ± 0.7	57 ± 9	–21.4	....	....	1,5
050223	0.5840	10 ± 4.6	109.6 ± 60.6	–20.0	....	....	1,6
050416	0.65	0.12 ± 0.02	25.1 ± 4.2	–20.3	1.0	1.17	1,9

NOTE: References: 1. Amati (2006a); 2. Le Floc'h et al. (2003); 3. Hammer et al. (2006); 4. Gorosabel J. et al. (2005); 5. Rau et al. (2005); 6. Pellizza et al. (2006); 7. Ghirlanda et al. (2007); 8. Ghirlanda et al. (2004); 9. Soderberg et al. (2007).

The redshift is plotted against $M_{\rm B}$ for our sample in Figure 1 (left-bottom panel). The diagram indicates that there is no clear trend of $M_{\rm B}$ on redshift in the range from $z = 0.2$ to $z = 2$. The upper panel of Figure 1 shows the distribution of $M_{\rm B}$ of the 24 LGRBs. Here $M_{\rm B}$ spans a range of $-16 \sim -22$ mag. In order to examine variation of the Amati relation with the luminosity of the LGRB's host, we separate the sample into two subgroups Groups L and H, according to the luminosity of the LGRB's host galaxy: Group L for LGRBs with $M_{\rm B} > -19.7$ and Group H for these with $M_{\rm B} \leq -19.7$ (see the vertical dashed line in Fig. 1). Each group contains 12 LGRBs. The bottom-right panel of Figure 1 shows the redshift distributions of the two groups (solid line for Group H and dashed line for Group L). In both groups, a majority of the LGRBs

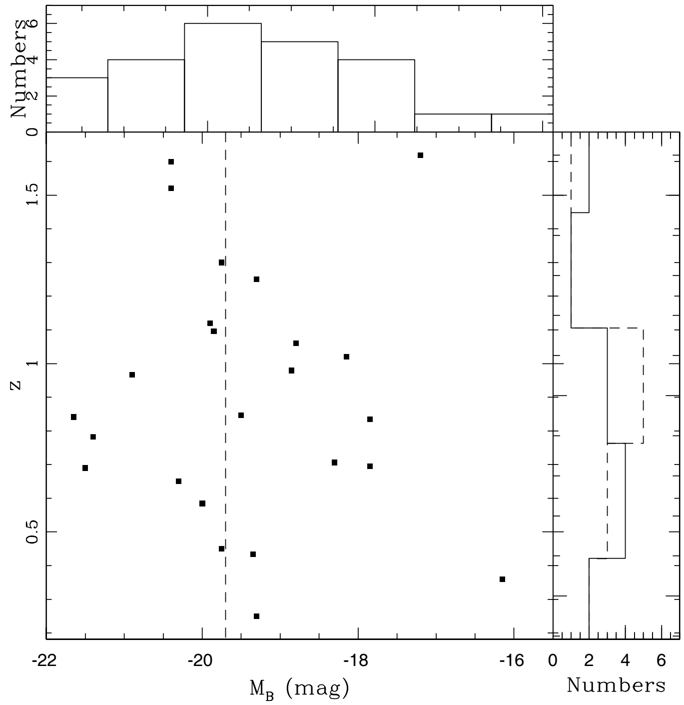

Fig. 1 *Bottom-left panel:* absolute B-band magnitude of LGRBs' host galaxies plotted against redshift. The vertical dashed line marks the value $M_{\rm B} = -19.7$ that divides the 24 LGRBs into two subgroups (see text for details). *Upper panel:*the distribution of absolute B-band magnitudes of the LGRBs' host galaxies. *Bottom-right panel:* distributions of redshift for the two subgroups (solid line for Group H, and dashed line for Group L).

are distributed in a narrow range from $z = 0.5$ to 1. A log-rank test indicates that redshift distributions of the two groups are drawn from the same parent population at a probability $\sim 70\%$.

Using 41 LGRBs with firmly determined $E_{\gamma,\rm iso}$ and $E_{\rm p}$, Amati (2006a) obtained an updated relation,

$$\log E_{\gamma,\rm iso} = a + b \log E_{\rm p}, \tag{1}$$

where $a = -3.35$ and $b = 1.75$ using the least squares method; and $a = -4.04$ and $b = 2.04$ using the maximum likelihood method. A least square fit to our 24 LGRBs as a single sample with Equation (1) leads to $a = -3.25 \pm 0.40$ and $b = 1.69 \pm 0.16$ with $\chi_r^2 = 1.60$. Here χ_r^2 is the reduced χ^2, defined as χ^2 of the fit divided by the degree of freedom. The fitting is shown in panel A of Figure 2. The two dashed lines in panel A mark the 1σ deviation of the best fit. This result is in good agreement with that obtained by Amati (2006) and Li (2007), which indicates that no obvious additional bias is introduced in the sample used in this paper by our sample selection.

Least square fittings are also carried out separately for Groups H and L. See Panels B and C of Figure 2. For Group H, the best-fit Amati relation has parameters $a = -2.97 \pm 0.73$ and $b = 1.61 \pm 0.30$ (with $\chi_r^2 = 1.96$), which is similar to $a = -3.47 \pm 0.44$ and $b = 1.74 \pm 0.17$ (with $\chi_r^2 = 0.94$) obtained for Group L, within the uncertainties. In addition to the best fit of the Amati relation, the dispersion around the best fit also provides important clues: the dispersion of Group H is slightly larger than that of the whole sample, while that of Group L is found to be significantly suppressed (see also the χ_r^2 for each group). Figure 3 shows the distributions of the deviations from the best fit in $\log E_{\gamma,\rm iso}$. The distribution for the whole sample, Group H and Group L, are shown in panels A, B and C, respectively. As shown in panel C,

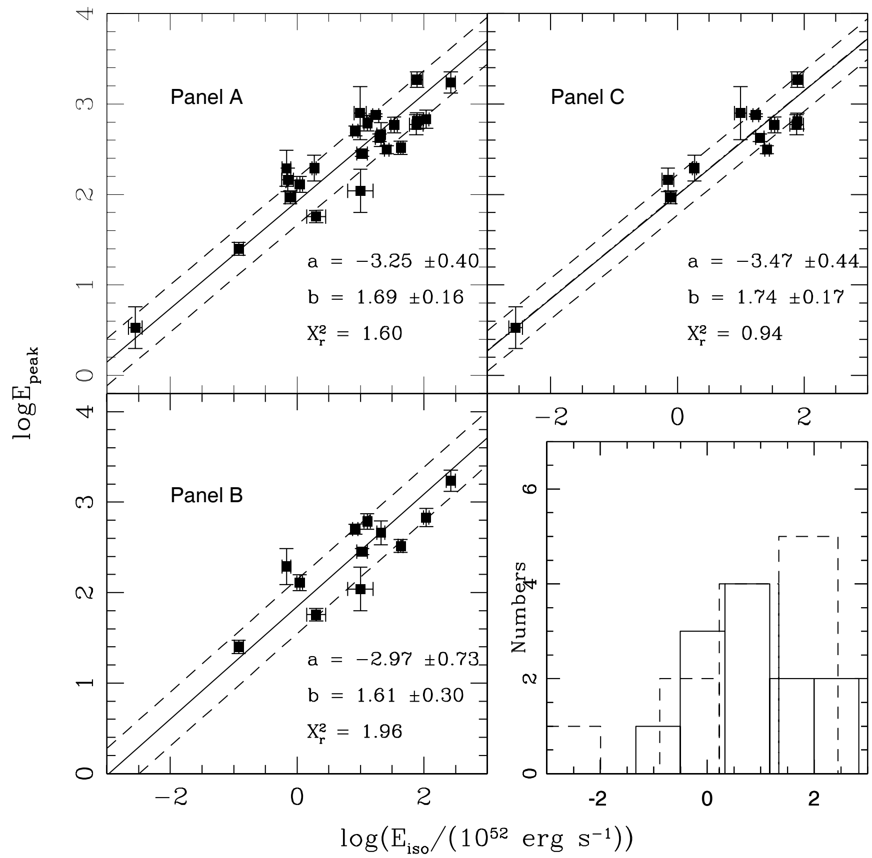

Fig. 2 Least squares fits (solid lines) to the whole sample of the 24 LGRBs (*Panel A*), and separately to Group H (*Panel B*) and Group L (*Panel C*). The two dashed lines in each panel mark the 1σ deviation from the best fit. *Right-bottom Panel*: Distributions of $\log E_{\gamma,\rm iso}$ for Group H and L. The symbols are the same as in Fig. 1.

the distribution of Group L is quite uniform with an obvious cut-off at ∼0.6. In contrast, Group H shows a relatively wider distribution with a clear peak at ∼0.5. The difference in the distribution of dispersions confirms the separation of the 24 LGRBs into the two subgroups, the origin of the difference is, however, out of the scope of this paper.

3 DISCUSSION AND SUMMARY

The number distribution of $\log E_{\gamma,\rm iso}$ for both subgroups is shown in the lower-right panel of Figure 2. The symbols are the same as in the right panel of Figure 1. Both subgroups have a similar dynamical range of $\log E_{\gamma,\rm iso}$, except that a sub-luminous LGRB (GRB 020903) is found only in Group L. The Amati relation is also fitted through Equation (1) after excluding the sub-luminous GRB 020903 from Group L. Then we obtain a relation with $a = -3.48 \pm 0.96$ and $b = 1.74 \pm 0.36$ ($\chi^2_r = 1.33$), which confirms the consistency of our fitting.

The L-Z relation has been firmly established in the local universe ($z < 1$) from various spectroscopic surveys (e.g., Tremonti et al. 2004; Savaglio et al. 2005; Liang et al. 2006). The L-Z relation indicates that in general high metallicity is found in luminous galaxies, and low metallicity in faint galaxies. Tremonti et al. (2004) obtained from SDSS a relationship $12 + \log({\rm O/H}) = -0.185 M_{\rm B} + 5.238$ with a typical

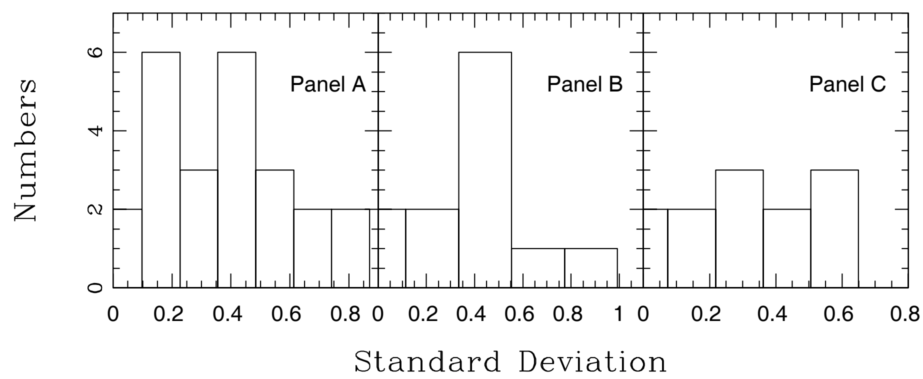

Fig. 3 *Panel A*: Distribution of deviations from the best fit for the whole sample. *Panel B* and *C*: The same for Group H and L, separately.

scatter of $\sigma 12 + \log(\mathrm{O/H}) = 0.16$. The existing observations indicate that local LGRBs' host galaxies are located not far from the L-Z relation (e.g., Savaglio et al. 2006). The median value of absolute magnitude is $M_\mathrm{B} = -20.35$ mag for Group H, and –18.55 mag for Group L. According to the relationship derived by Tremonti et al. (2004), the difference of metallicity is inferred to be 0.33 dex which is two times larger than the dispersion of the L-Z relation. Recent observations revealed an evolution of the zero point of the L-Z relation from the local universe to intermediate redshift $z = 1$. Different degrees of evolution are found by various authors. For instance, Liang et al. (2006) found an evolution of 0.3 dex since $z = 0.65$, while a much more moderate evolution of 0.14 dex is reported by Kobulnicky & Kewley (2004). In the present work, the cosmological evolution is not a key issue because a majority of LGRBs in *both* of the two subgroups are uniformly distributed in a relatively narrow dynamical range of redshift (from $z = 0.5$ to $z = 1$, see Fig. 1). According to these existing observations, the consistency of the Amati relation for different luminosity host galaxies implies that the Amati relation does not vary strongly with the metallicity of the LGRB's environment.

In the generally accepted fireball model, the Amati relation could be explained by the standard internal shock scenario, $E_\mathrm{p} \propto \Gamma^{-2} L^{1/2} t_\mathrm{var}^{-1}$, where Γ is the fireball bulk Lorentz factor, L is the GRB luminosity and t_var is a typical variability time scale (e.g., Zhang & Mészáros 2002; Rees & Mészáros 2005; Ryde 2005). The agreement of the Amati relations in the two subgroups would consequently require that both Γ and t_var are approximately independent on the environment's metallicity. An alternative explanation of the Amati relation is the thermal radiation from photosphere of GRB (e.g., Rees & Mészáros 2005; Thompson 2006; Thompson et al. 2007). In this context, one expects $E_\mathrm{p} \propto R_0^{-1/2} \Delta t_\mathrm{j}^{-1/4} E_{\gamma,\mathrm{iso}}^{1/2}$, where R_0 is the radius of complete thermalization. This radius is reasonably assumed to be comparable or less than the radius of core of the progenitor. Because of the weak dependence on the duration of prompt emission, the slope of the Amati relation primarily depends on the radius. Our test therefore implies a similar core radius of progenitor in both subgroups.

The result obtained in this paper differs from that in Li (2007), who found variation of the Amati relation when separating the whole sample into four groups according to redshift. However, various selection bias should be carefully considered in such studies. Instead of the E_p-$E_{\gamma,\mathrm{iso}}$ relation, a much lower dispersion is found in the E_p-E_γ relation by correcting for the collimation angles of jet (Ghirlanda et al. 2004, 2007). The different slope between the E_p-$E_{\gamma,\mathrm{iso}}$ and E_p-E_γ relations leads to the hypothesis that powerful bursts intrinsically have smaller opening angles (Ghirlanda et al. 2005). Assuming the E_p-E_γ relation is intrinsic for all LGRBs, a dependence of the opening angle on the burst energy could be a possible explanation of the decrease of slope of the Amati relation with redshift, because sub-luminous bursts have been only detected in local universe up to now.

If, following Ghirlanda et al. (2005), we assume that the E_p-E_γ relation is intrinsic for all LGRBs, then it is possible to compare the properties of the burst environment in the two subgroups. So far, uncertainties of the burst environment have not been considered in the previous studies on the $E_{\rm p}$-E_γ relation. Moreover, the properties of the circumburst medium could provide some insight about the energy source of LGRB. The model of the LGRB afterglow light curves indicates that a homogeneous medium is more favored than a wind-like r^{-2} radial stratification (e.g., Panaitescu 2005; and recently summarized in Fryer et al. 2007). The observed homogeneous medium could be explained by either termination shock of wind (Wijers 2001), or bubbles with uniform density produced in an intense starburst region (Chevalier et al. 2004).

In the homogeneous case, the density is (Sari 1999)

$$n = \frac{E_{\gamma,{\rm iso},52}}{\eta}\left(\frac{\theta_{\rm j}}{0.161}\right)^{8}\left(\frac{t_{\rm j}}{1+z}\right)^{-3}\ {\rm cm}^{-3}, \tag{2}$$

where $\theta_{\rm j}$ is the opening angle of the jet, η is the radiation efficiency which is usually assumed to be the same for all bursts at $\eta = 0.2$ (Frail et al. 2001) and $t_{\rm j}$ is the break time of the afterglow light curve in units of days. The estimated density is shown in column (7) of Table 1 for the 11 LGRBs with firm estimates of jet break times (as shown in column (6) of Table 1). For all the 11 LGRBs, the inferred values of density are consistent with the observations. The measured density roughly extends from 1 to 10 ${\rm cm}^{-3}$ (e.g., Frail et al. 2001; Panaitescu & Kumar 2002; Schaefer et al. 2003). Comparing the density between Groups H and L, it is noted that the distribution of density in Group L is roughly concentrated around the value of $2\,{\rm cm}^{-2}$, while the density is more spread out in Group H.

We note here that our treatment of binning the sample into two subgroups according to the B-band luminosity of the host galaxies is a more or less simplified treatment. The B-band luminosity is not a perfect indicator of stellar mass (or metallicity) because it suffers from extinction and traces only the mass of massive stars. More accurate binning and direct measurement of metallicity are required to accurately test the evolution of the Amati relation.

In summary, we have examined the systematics of the Amati relation by dividing the 24 LGRBs into two subgroups according to the absolute B-band magnitudes of their host galaxies. No obvious difference is found in the Amati relations of the two subgroups, within the uncertainties, although their deviations from the best fit seem to have different distributions. Combining with the well established luminosity - metallicity relation, the present study does not imply strong evolution of the Amati relation with the LGRB's environmental metallicity.

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