IDENTIFICATION OF TWO CATEGORIES OF OPTICALLY BRIGHT $\gamma$-RAY BURSTS

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ABSTRACT

We present the results of a systematical analysis of the intrinsic optical afterglow light curves for a complete sample of gamma-ray bursts (GRBs) observed in the period from Feb. 1997 to Aug. 2005. These light curves are generally well-sampled, with at least four detections in the $R$ band. The redshifts of all the bursts in the sample are available. We derive the intrinsic $R$ band afterglow lightcurves (luminosity versus time within the cosmic proper rest frame) for these GRBs, and discover a fact that they essentially follow two universal tracks after 2 hours since the GRB triggers. The optical luminosities at 1 day show a clear bimodal distribution, peaking at $1.4 \times 10^{46}$ erg s$^{-1}$ for the luminous group and $5.3 \times 10^{44}$ ergs s$^{-1}$ for the dim group. About 75% of the GRBs are in the luminous group, and the other 25% belong to the dim group. While the luminous group has a wide range of redshift distribution, the bursts in the dim group all appear at a redshift lower than 1.1.

Subject headings: gamma rays: bursts—gamma rays: observations—methods: statistical

1. INTRODUCTION

Gamma-ray bursts (GRBs) are believed to be the brightest electromagnetic explosions in the universe after the identification of their cosmic origin (Metzger et al. 1997). Two categories of these erratic, transient events have been identified, i.e. long-soft and short-hard (Kouveliotou et al. 1993). The association of long GRBs with very energetic core-collapse supernovae has now been well established (Galama et al. 1998; MacFadyen et al. 1999; Bloom et al. 1999; Stanek et al. 2003; Hjorth et al. 2005; Thomsen et al. 2004; Malesani et al. 2004). Several short GRBs have been localized and observed by Swift and HETE-2 recently, which are found to reside in nearby galaxies, some of which are of early-type with little star formation (Gehrels et al. 2005; Fox et al. 2005; Villasenor et al. 2005; Hjorth et al. 2005a; Barthelmy et al. 2005; Berger et al. 2005). This indicates that they have a distinct origin from the long species. Most of the well localized GRBs, both long and short, are followed by long-lived, decaying afterglows in longer wavelengths (Costa et al. 1997; Paradijs et al. 1997; Frail et al. 1997; Gehrels et al. 2005; Fox et al. 2005). Long GRBs have been themselves classified into two groups, optically bright and optically dark, based on whether or not an optical transient is detected to a given brightness limit at a given time delay (e.g. Groot et al. 1998; Fynbo et al. 2001; Berger et al. 2002; Jacobsson et al. 2004; Rößl et al. 2005). The origin of optically dark GRBs is still unclear. Very early, tight upper limits made by the Swift UV-Optical Telescope indicate that the darkness is not caused by observational biases (Roming et al. 2005). Based on X-ray afterglow data, a tentative bimodal distribution of X-ray luminosities has been also noticed (Böer & Gendre 2000; Gendre & Böer 2005).

Over more than 8 years of optical afterglow hunting, more than 70 optically-bright GRBs have been detected, among which 44 bursts have well-sampled light curves and redshift measurements (§2). In this Letter we present a systematical analysis to these 44 optical afterglow light curves in the cosmic rest frame. We find a fact that their late-time lightcurves follow two apparent universal tracks (§3). We then conclude that within the optically bright GRBs there exist two sub-categories, the luminous group and the dim group (§4). Cosmological parameters $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 71$ km Mpc$^{-1}$ s$^{-1}$ have been adopted throughout this Letter.

2. DATA

We make a complete search from the literature for the $R$-band afterglow light curves detected during the time period from Feb. 1997 to Aug. 2005. We obtain a GRB sample with 44 GRBs, which is tabulated in Table 1. These light curves have at least four detections in the $R$-band. The redshifts of the bursts are available. We collect the following data for these bursts from published papers or from GCN reports if the former are not available, i.e. redshift ($z$), $R$-band magnitude, spectral index ($\beta$), and extinction by the host galaxy ($A_V$). For those bursts whose $\beta$ and $A_V$ are not available, we take $\beta = 0.75$, the mean value of $\beta$ in our sample, and $A_V = 0$. Galactic extinction correction is made by using a reddening map presented by Schlegel et al. (1998). The extinction curve of the Milky Way (Pei 1992) is adopted to calculate the extinction in the local frame of the GRB host galaxy. The $k$-correction in magnitude is calculated by $k = -2.5(\beta - 1) \log(1 + z)$. For late time data, possible flux contribution from the host galaxy is subtracted.

3. THE BIMODAL LUMINOSITY EVOLUTIONS

$^1$A full version of the GRB sample with references to the observational data are available in the electronic version

$^2$We collect the $\beta$ and the extinction $A_V$ of each burst from the same literature to reduce the uncertainties introduced by different authors.

$^3$We also tried other types of extinction curves, and found that our results are insensitive to the extinction model adopted.
We convert the corrected magnitudes to fluxes ($F_c$) by using the photometric zero points given by Fukugita et al. (1995). The luminosity at the cosmic proper time $t'$, $L_R(t')$, is calculated by $L_R(t') = 4\pi D_L^2(z) F_c$, where $D_L(z)$ is the luminosity distance at $z$. The luminosity error is calculated by $\Delta \log L_R = 0.16(\Delta R^2 + \Delta A_R^2) + [\Delta \log (1+z)]^2/2$, where $\Delta R$ is the observed uncertainty of the $R$ band magnitude, $\Delta A_R$ is the uncertainty of the host galaxy extinction at the cosmic rest frame wavelength $\lambda_{R*} = \lambda_R/(1+z)$, and $[\Delta \log (1+z)]^2$ is the error of the k-correction.

The intrinsic R-band light curves [$L_R(t')$ vs. $t'$] are displayed in Figure 1 for 42 bursts. The two nearby GRBs, 980425 and 031203 are not included, since their light curves are significantly contaminated by the underlying supernova component (Galama et al. 1998; Thomsen et al. 2004). It is found that although the light curves at $t' < 0.1$ days vary significantly, they are clustered and follow two apparent universal tracks at $t' > 0.1$ days, indicating that within the optically bright GRBs there exist two well-separated sub-categories. The majority of the bursts ($\sim 75\%$) comprises an optically luminous GRB group, which includes the well-studied GRBs such as 030329, 990123 and 990510. It is interesting that although the isotropic gamma-ray energy ($E_{\gamma,iso}$) of GRB 990123 and GRB 030329 differ by almost 2 orders of magnitude, their late optical afterglow luminosities are similar.$^4$ The other $\sim 25\%$ GRBs in our GRB sample comprises the dim group, with the representative bursts being GRBs 021211 and 041006. We zoom in these light curves in the time regime from 0.1 days to 10 days in the inset of Figure 1. The bimodal lightcurve trajectories during this are more clearly visible. Based on the separation of the two groups by the luminosity at 1 day ($\log L_{R,1d}/\text{erg cm}^{-2} = 45.15$, see Figure 2) and adopting a typical temporal decay index $\sim -1.2$, we draw a division line for the two groups as $\log L_R = 45.15 - 1.2 \log t'$ (the dashed line in Figure 1). It is found that 25 (out of 34) and 7 (out of 10) light curves in the luminous and dim groups, respectively, cover this time regime and do not cross over the division line. They are the most representative (with the smallest scatter) ones in both groups. The bursts in the luminous group are typically brighter than those in the dim group by a factor of $\sim 30$.

We read off or extrapolate/interpolate the luminosity at a given epoch from the light curves, and perform rigorous statistics to access the bimodality of our sample. We first select the intrinsic luminosity at 1 day for our purpose. Our consideration is two folds. First, the early optical light curves may have contributions from the reverse shock component or additional energy injection from the central engine. The optical band may be below the cooling frequency or even below the typical synchrotron frequency so that the flux sensitively depends on many unknown shock parameters. On the other hand, the late emission is fainter and may contain luminosity contamination from the host galaxy. Second, most of the observations were made around this epoch. This makes the luminosity derivations more reliable. Figure 2 shows the 2-dimensional distribution of the intrinsic R-band luminosity at 1 day$^5$, $L_{R,1d}$, versus $E_{\gamma,iso}$ (panel a), and the distributions of the two quantities, respectively (panels b and c). Flux thresholds in both the $\gamma$-ray and the optical bands introduce selection effects against low-energy, low-luminosity bursts, and these are indicatively marked as the grey regions in Figure 2. There are three most prominent outliers whose light curves deviate from the universal light curves, i.e. GRBs 970508, 030226, and 050408. They are excluded in the statistical analyses (see more detailed discussion in §4). While the $E_{\gamma,iso}$ distribution displays a power-law with sharp cutoff around $10^{51.5}$ ergs (due to the selection effect), $\log L_{R,1d}$ shows a well-defined bimodal distribution, which is well fitted by a two Gaussian model centered at $\log L_{c,1} = 44.66$ with $\sigma_1 = 0.41$ and $\log L_{c,2}/\text{erg s}^{-1} = 46.15$ with $\sigma_2 = 0.77$. The bimodality is at a confidence level of $3\sigma$ tested by a classification algorithm with the minimum Euclidian distance discriminant and the KMM algorithm (Ashman et al. 1994). A bootstrap test ($10^5$ bootstrap samples) shows that the distributions of the means of $\log L_{R,1d}$ of the two groups and their covariance (c) are normal, which gives $\log L_{c,1}/\text{erg s}^{-1} = 44.72^{+0.36}_{-0.36}$, $\log L_{c,2}/\text{erg s}^{-1} = 46.15^{+0.14}_{-0.20}$, and $c = 0.11^{+0.16}_{-0.06}$ at $3\sigma$ significance level. These results indicate that the bimodality is not due to statistical fluctuations.

In order to further examine the bimodal distribution at different epochs, we also derive the distributions at $\log t'/1\text{day} = -0.5$ and 0.5, respectively. We find that the distribution of the luminosities at $\log t'/1\text{day} = 0.5$ is bimodal with a $3\sigma$ significance level. The bimodality of the luminosity distribution at $\log t'/1\text{day} = -0.5$ has a lower (i.e. $2\sigma$) statistical significance. Nonetheless, the distribution still stands with a gap at $\log L_{R}/\text{erg s}^{-1} = 45.5$. The lower significance is expected, because of the various factors (e.g. reverse shock, early injection, etc) concerning the early afterglows.

4. CONCLUSIONS AND DISCUSSION

We have derived the intrinsic $R$ band afterglow lightcurves within the cosmic proper rest frame with a completed sample observed from Feb. 1997 to Aug. 2005. These light curves follow two apparent universal tracks after 2 hours since the GRB triggers. The optical luminosity at 1 day clearly shows a bimodal distribution, with the peak luminosities being $1.4 \times 10^{50}$ erg s$^{-1}$ for the luminous group and $5.3 \times 10^{44}$ ergs s$^{-1}$ for the dim group.

One interesting feature for the dim group is that these bursts all appear to have low redshifts. It has been previously speculated that nearby GRBs might be different from their cosmological brethren (Norris 2002; Soderberg et al. 2004; Guetta et al. 2004). In our sample, the two well-known nearby GRBs, 980425 and 031203, both belong to the dim group. Except GRB 980613 ($z = 1.096$) and GRB 021211 ($z = 1.006$), other bursts in the dim

$^4$We notice that Nardini et al. (2005) independently obtained the same result during the process when our paper was being reviewed.

$^5$In view of the difficulty of subtracting the supernova contribution from GRB 980425 (Galama et al. 1998) and GRB 031203 (Thomsen et al. 2004), we use the first two data points (which are around 1 day) in each burst’s light curve to derive the upper limits of their luminosities at 1 day, both giving $\sim 7 \times 10^{43}$ erg s$^{-1}$. The Galactic extinction corrected luminosities are $8.3 \times 10^{43}$ erg s$^{-1}$ for GRB 980425 and $9.2 \times 10^{44}$ erg s$^{-1}$ for GRB 031203.
group all have $z < 1$. Besides the low-$z$ property, the bursts in the dim group all have an isotropic $\gamma$-ray energy much lower than that of the bursts in the luminous group. They also have simple lightcurves. All the bursts in the dim group have a single gamma-ray pulse, except for GRB 990712 who has two well-separated pulses. We notice that the observed $R$-band magnitudes for the dim GRBs are generally $\sim (21 - 22.5)$ mag a few days after the trigger. Although a burst with log($L_R$/erg s$^{-1}$) = 44.72 (the typical 1-day optical luminosity for the dim group) should be detected up to $z = 2.4$ for an observation threshold of $R \sim 22.5$ mag, the efficiency to detect optical transients fainter than $R \sim 21$ is dramatically reduced. The observational bias for the deficit of high-redshift, optical-dim GRBs thus cannot be ruled out.

The extinction effects have been carefully taken into account. The data indicate that the dim GRBs do not exhibit significantly higher extinction than the luminous ones. It has been suggested that dust in the host galaxy may be destroyed by early radiation from $\gamma$-ray bursts and their afterglows (Waxman et al. 2000; Fruchter et al. 2001). It is found that the optical extinctions are $10 - 100$ times smaller than what are expected from the X-ray absorption (Galama et al. 2001), and that the dimness of GRB 021211, a representative burst in our dim group, could not be explained by the extinction effect (Holland et al. 2004). The apparent bimodality therefore could not be interpreted by the extinction effect. Our results then suggest that there might be two types of progenitors or two types of explosion mechanisms in operation.

Some GRBs show an initial shallow decay before landing onto the luminous branch. GRB 970508 is the most prominent one. The light curve is initially almost flat before re-brightening at about 0.5 days, peaks at 1 day, and eventually settles onto the luminous branch, although with significant fluctuations (Pedersen et al. 1998). These fluctuations are similar to those observed in GRBs 000301C, 021004, and 030329. The initial shallow decay and fluctuations are thought to be due to additional energy injections during the afterglow phase (Dai & Lu 2001; Björnsson et al. 2004; Fox et al. 2003; Zhang et al. 2005). GRBs 050408 and 050319 have the similar behavior. When injection is essentially over, the total afterglow kinetic energies of these bursts are similar to those of the bursts in the luminous group. Therefore they should be classified into the luminous group. Another type of outliers are those light curves with a sharp rapid decay at early times. GRB 030226 is the most prominent one in our sample. This may be attributed by an early jet break, and the rapid decay effect is due to the sideways expansion of the jet, which significantly reduces the optical luminosity (Rhoads 1999).

The two apparent universal lightcurve tracks at later times are intriguing. It is widely believed that afterglows are synchrotron emission from shocked circumburst medium as the fireball is decelerated (Mészáros & Rees 1997; Sari et al. 1998; see also reviews by Mészáros 2002, Zhang & Mészáros 2004, Piran 2005). At a late enough epoch, the optical band may be above both the typical synchrotron frequency and the synchrotron cooling frequency. In such a spectral regime and at a particular epoch (e.g. $t' = 1$ d), the optical luminosity $L_{R,1d} \propto E_{\text{iso}}^{(p+2)/4} \epsilon_e^{-1} \epsilon_B^{(p-2)/4}$, where $E_{\text{iso}}$ is the isotropic kinetic energy of the fireball, $\epsilon_e$ and $\epsilon_B$ are shock energy equipartition factors for electrons and magnetic fields, respectively, and $p$ is the electron spectral index. We can see that $L_{R,1d}$ is medium-density-independent, and only weakly depends on $\epsilon_B$. The universal afterglow luminosity therefore suggests that both $E_{\text{iso}}$ and $\epsilon_e$ are standard values around 1 day for each subclass. A standard $\epsilon_e$ suggests universal properties of relativistic shocks. A standard $E_{\text{iso}}$ on the other hand, is intriguing, since $E_{\gamma}$ varies for 4 orders of magnitude among long duration GRBs and they generally follow a power-law distribution with a cutoff at low luminosity end (Schmidt 2001, Norris 2002). They become standard only when jet beaming correction is taken into account (Frail et al. 2001). Our results are consistent with the picture that GRBs with a higher $E_{\text{iso}}$ tends to have a higher $\gamma$-ray emission efficiency (Lloyd-Ronning et al. 2004). The $E_{\text{iso}}$ derived using 10-hour X-ray data requires a jet beaming correction to achieve a standard value (Berger et al. 2003). The early X-ray afterglows in the cosmic proper frame for a group of GRBs observed with the Swift X-Ray Telescope indicate a large scatter of $E_{\text{iso}}$ at early time (Chincarini et al. 2005). Our results therefore suggest a possible evolution of $E_{\text{iso}}$ with time. One scheme might be that GRB jets are initially structured (Zhang & Mészáros 2002; Rossi et al. 2002), and the early $\gamma$-ray and X-ray properties are sensitive to the observer's viewing angle. The jet structure tends to smear out with time, so that at later times, the outflow is more isotropic and the viewing angle effect no longer plays an essential role.

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Table 1

| GRB   | $z$  | $\beta(\Delta \beta)$ | $A_{V, host}(\Delta A_{V, host})$ | GRB   | $z$  | $\beta(\Delta \beta)$ | $A_{V, host}(\Delta A_{V, host})$ |
|-------|-----|------------------------|-----------------------------------|-------|-----|------------------------|-----------------------------------|
| 970228 | 0.695 | 0.780(0.022) | 0.5 | 970508 | 0.835 | 1.11 | 0 |
| 971214 | 3.42  | 0.87(0.13) | 0.43 (0.08) | 980326 | 1.0  | 0.8(0.4) | 0 |
| 980425 | 0.0085 | - | - | 980613 | 1.096 | 0.60 | 0.45 |
| 980703 | 0.966 | 1.013 (0.016) | 1.50 (0.11) | 990123 | 1.6004 | 0.750 (0.068) | 0 |
| 990510 | 1.6187 | 0.55 | 0 | 990712 | 0.434 | 0.99 (0.02) | 0 |
| 991208 | 0.706 | 0.75 | 0 | 991216 | 1.02 | 0.60 | 0 |
| 990313 | 4.5 | 0.70 | 0.18 | 000301C | 0.0085 | - | - |
| 990613 | 1.118 | 0.75 | 0.96 | 000926 | 1.09 | 0.60 | 0 |
| 011121 | 0.36 | 0.80(0.15) | 0 | 000926 | 2.066 | 1.00(0.18) | 0.18(0.06) |
| 020124 | 3.198 | 0.91 (0.14) | 0 | 030326 | 2.066 | 1.00(0.18) | 0.18(0.06) |
| 020813 | 1.25 | 0.85(0.07) | 0.14(0.04) | 011211 | 0.36 | 0.80(0.15) | 0 |
| 021004 | 2.335 | 0.39 | 0.3 | 0209303 | 0.25 | - | - |
| 030226 | 1.98 | 0.70(0.03) | 0 | 030329 | 0.17 | 0.5 | 0.30(0.03) |
| 030328 | 1.52 | - | - | 030429 | 2.65 | 0.75 | 0.34 |
| 031203 | 0.105 | - | - | 040924 | 0.859 | 0.70 (0) | 0 |
| 041006 | 0.716 | 0.55 | 0 | 050319 | 3.24 | - | - |
| 050408 | 1.24 | - | - | 050525 | 0.606 | 0.97(0.10) | 0.25(0.16) |
| 050730 | 3.97 | - | - | 050730 | 2.65 | 2.615 | - |

a GRBs marked as bold fonts belong to the low-optical-luminosity group, with separation at $L_{R,1d} \sim 1.4 \times 10^{45}$ erg. s$^{-1}$ (see Figure 2).

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Fig. 1.— The R-band light curves \( (L_R(t') \text{ vs. } t') \) in the cosmic proper rest frame. The dashed line is a division of the two groups of GRBs, \( \log L_R = 45.15 - 1.2 \log t' \). The upper inset zooms in the light curves in the time regime from 0.1 days to 10 days. Those bursts marked with blue color in the figure legend belong to the dim group.
Fig. 2.— The 2-dimensional distribution of $L_{R,1d}$ and $E_{\gamma,iso}$ (panel a), as well as the distributions of both quantities (panels b and c) for the bursts in our sample. The significant outliers, GRBs 030226, 970508, and 050408 have been excluded. The $E_{\gamma,iso}$ has been corrected to the band pass $20 - 2000$ keV in the rest frame according to the spectral parameters of prompt gamma-ray emission. The circled-crosses are the means of the two quantities for the two groups (excluding those bursts with limits). The grey area marks the parameter region in which the flux-threshold selection effect plays a dominant role. The dotted line in panel (b) is the best fit using a two Gaussian model. The perpendicular dotted-line is the separation between the dim and the luminous groups in the two Gaussian model.
Appended below is the full version of Table 1 with references to the observational data. It is available in the electronic version in ApJ Letters.

| GRB | $z$   | $\beta (\Delta \beta)$ | $A_{V,\text{host}} (\Delta A_{V,\text{host}})$ | Ref\(^b\) |
|-----|-------|--------------------------|-----------------------------------------------|----------|
| 970228 | 0.695 | 0.780(0.022)             | 0.5                                           | 1:2:2-3  |
| 970508 | 0.835 | 1.11                     | 0                                             | 4:5:5-6  |
| 971214 | 3.42  | 0.87(0.13)               | 0.43 (0.08)                                   | 7:8:8-9  |
| 980326 | 1.0   | 0.8(0.4)                 | 0                                             | 10:10:10-11 |
| 980425 | 0.0085 | -                        | -                                             | 12::13  |
| 980613 | 1.096 | 0.60                     | 0.45                                          | 14:15:15 |
| 980703 | 0.966 | 1.013 (0.016)            | 1.50 (0.11)                                   | 16:17:17-20 |
| 990123 | 1.6004 | 0.750 (0.068)           | 0                                             | 21:22:22-24 |
| 990510 | 1.6187 | 0.55                     | 0                                             | 25:26:26-28 |
| 990712 | 0.434 | 0.99 (0.02)              | 0                                             | 25:29:29-30 |
| 991208 | 0.706 | 0.75                     | 0                                             | 31:32:32 |
| 991216 | 1.02  | 0.60                     | 0                                             | 33:33:33:34 |
| 000131 | 4.5   | 0.70                     | 0.18                                          | 35:35:35 |
| 000301C | 2.03  | 0.70                     | 0.09                                          | 36:37:37 |
| 000418  | 1.118 | 0.75                     | 0.96                                          | 38:39:39 |
| 000911 | 1.058 | 0.724(0.006)             | 0.39                                          | 40:41:41-42 |
| 000926 | 2.066 | 1.00(0.18)               | 0.18(0.06)                                    | 43:44:44 |
| 010222 | 1.477 | 1.07 (0.09)              | 0                                             | 45:46:46 |
| 011121 | 0.36  | 0.80(0.15)               | 0                                             | 47:48:48 |
| 01121  | 2.14  | 0.56(0.19)               | 0.08(0.08)                                    | 49:50:51-54 |
| 020124 | 3.198 | 0.91 (0.14)              | 0                                             | 55:55:55-56 |
| 020405 | 0.69  | 1.43(0.08)               | 0                                             | 57:58:58-59 |
| 020813 | 1.25  | 0.85(0.07)               | 0.14(0.04)                                    | 60:61:61-62 |
| 020903 | 0.25  | -                        | -                                             | 63::63  |
| 021004 | 2.335 | 0.39                     | 0.3                                           | 64:65:65-66 |
| 021211 | 1.01  | 0.69                     | 0                                             | 67:68:68-70 |
| 030226 | 1.98  | 0.70(0.03)               | 0                                             | 71:72:72-73 |
| 030323 | 3.372 | 0.89(0.04)               | < 0.5                                         | 74:74:74 |
| 030328 | 1.52  | -                        | -                                             | 75::76-83 |
| 030329 | 0.17  | 0.5                      | 0.30(0.03)                                    | 84:85:85-87 |
| 030429 | 2.65  | 0.75                     | 0.34                                          | 88:89:89 |
| 030723 | 2.10  | 1.0                      | 0.4                                           | 90:90:90 |
| 031203 | 0.105 | -                        | -                                             | 91::92  |
| 040924 | 0.859 | 0.70 (0)                 | 0.16                                          | 93:94:94-101 |
| 041006 | 0.716 | 0.55                     | 0                                             | 102:102:102 |
| 050315 | 1.949 | -                        | -                                             | 104::105:107 |
| 050319 | 3.24  | -                        | -                                             | 108::109-115 |
| 050401 | 2.90  | -                        | -                                             | 116::117-121 |
| 050408 | 1.24  | -                        | -                                             | 122::123-128 |
| 050502 | 3.793 | -                        | -                                             | 129::130 |
| 050525 | 0.606 | 0.97(0.10)               | 0.25(0.16)                                    | 131:132:132-133 |
| 050730 | 3.97  | -                        | -                                             | 134::134-141 |
| 050820 | 2.615 | -                        | -                                             | 142::143-148 |

Notes:

a GRBs marked as bold font belong to the low-optical-luminosity group; others belong to the high-optical-luminosity group.

b References: three groups of references separated by semicolons are for $z; \beta$ and host galaxy extinction; light curve data, respectively. A hyphen is marked when no reference is available.
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