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IDENTIFICATION OF TWO CATEGORIES OF OPTICALLY BRIGHT GAMMA-RAY BURSTS

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ABSTRACT

We present the results of a systematic analysis of the intrinsic optical afterglow light curves for a complete sample of gamma-ray bursts (GRBs) observed in the period from 1997 February to 2005 August. 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 light curves (luminosity vs. time within the cosmic proper rest frame) for these GRBs and discover that they essentially follow two universal tracks beyond 2 hours after the GRBs triggered. The optical luminosities at 1 day show a clear bimodal distribution, peaking at 1.4×10^{46} ergs s^{-1} for the luminous group and 5.3×10^{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 widely distributed range of redshifts, the bursts in the dim group all appear at redshifts lower than 1.1.

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

Online material: machine-readable table

1. INTRODUCTION

Gamma-ray bursts (GRBs) are believed to be the brightest electromagnetic explosions in the universe, now that their cosmic origin has been identified (Metzger et al. 1997). Two categories of these erratic, transient events have been identified, that is, long-soft and short-hard (Kouveliotou et al. 1993). The association of long GRBs with very energetic core-collapse supernovae has since been well established (Galama et al. 1998; MacFadyen et al. 1999; Bloom et al. 1999; Stanek et al. 2003; Hjorth et al. 2003; Thomsen et al. 2004; Malesani et al. 2004). Several short GRBs have been localized and observed by *Swift* and *HETE-2* recently and were found to reside in nearby galaxies, some of which are of early type, with little star formation (Gehrels et al. 2005; Bloom et al. 2006; Fox et al. 2005; Villasenor et al. 2005; Hjorth et al. 2005; Barthelmy et al. 2005; Berger et al. 2005). This indicates that they have an origin distinct from that of the long species. Most of the well-localized GRBs, both long and short, are followed by long-lived, decaying afterglows at longer wavelengths (Costa et al. 1997; van Paradijs et al. 1997; Frail et al. 1997; Gehrels et al. 2005; Fox et al. 2005). Long GRBs have themselves been classified into two groups, optically bright and optically dark, based on whether or not an optical transient is detected to a given brightness limit after a given delay (see, e.g., Groot et al. 1998; Fynbo et al. 2001; Berger et al. 2002; Jakobsson et al. 2004; Rol et al. 2005). The origin of optically dark GRBs is still unclear. Very early time, tight upper limits obtained with 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 also been noted (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 systematic analysis of these 44 optical afterglow light curves in the cosmic rest frame. We find that their late-time light curves follow two apparent universal tracks (§ 3). We then conclude that within the optically bright GRBs there exist two subcategories, a luminous group and a 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.

2. DATA

We made a complete search of the literature for the *R*-band afterglow light curves detected during the time period from 1997 February to 2005 August. We obtained a GRB sample with 44 GRBs, which is listed in Table 1. These light curves have at least four detections in the *R* band. The redshifts of the bursts are available. We collected the following data for these bursts from published papers or from GRB Coordinates Network reports if the former were not available: redshift (z), *R*-band magnitude, spectral index (β), and extinction by the host galaxy (A_V).[3] For those bursts that did not have available values of β and A_V, we take $\beta = 0.75$, the mean value of β in our sample, and $A_V = 0$. Correction for Galactic extinction was made by using the reddening maps presented by Schlegel et al. (1998). The extinction curve of the Milky Way[4] (Pei 1992) was adopted to calculate the extinction in the local frame of the GRB host galaxy. The k-correction in magnitude is calculated as $k = -2.5(\beta - 1)\log(1 + z)$. For late-time data, a possible flux contribution from the host galaxy is subtracted.

3. BIMODAL LUMINOSITY EVOLUTION

We convert the corrected magnitudes to fluxes (F^c) by using the photometric zero points given by Fukugita et al. (1995). The luminosity at cosmic proper time t', $L_R(t')$, is calculated as $L_R(t') = 4\pi D_L^2(z)F^c$, where $D_L(z)$ is the luminosity distance at z. The luminosity error is calculated as $\Delta \log L_R = \{0.16 \times (\Delta R^2 + \Delta A_{R'}^2) + [\Delta\beta \log(1 + z)]^2\}^{1/2}$, where ΔR is the observed uncertainty in the *R*-band magnitude, $\Delta A_{R'}$ is the uncertainty

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[3] We collected the β and the extinction A_V of each burst from the same reference to reduce the uncertainties introduced by using different authors.

[4] We also tried other types of extinction curves and found that our results are insensitive to the extinction model adopted.

TABLE 1
GRBs with Well-sampled Optical Afterglow Light Curves and Known Redshifts

GRB	z	β	$A_{V,\mathrm{host}}$	GRB	z	β	$A_{V,\mathrm{host}}$
970228	0.695	0.780 (0.022)	0.5	020813	1.25	0.85 (0.07)	0.14 (0.04)
970508	0.835	1.11	0	020903[a]	0.25	...	...
971214	3.42	0.87 (0.13)	0.43 (0.08)	021004	2.335	0.39	0.3
980326[a]	1.0	0.8 (0.4)	0	021211[a]	1.01	0.69	0
980425[a]	0.0085	...	...	030226	1.98	0.70 (0.03)	0
980613[a]	1.096	0.60	0.45	030323	3.372	0.89 (0.04)	<0.5
980703	0.966	1.013 (0.016)	1.50 (0.11)	030328	1.52	...	...
990123	1.6004	0.750 (0.068)	0	030329	0.17	0.5	0.30 (0.03)
990510	1.6187	0.55	0	030429	2.65	0.75	0.34
990712[a]	0.434	0.99 (0.02)	0	030723	2.10	1.0	0.4
991208	0.706	0.75	0	031203[a]	0.105	...	...
991216	1.02	0.60	0	040924[a]	0.859	0.70 (0)	0.16
000131	4.5	0.70	0.18	041006[a]	0.716	0.55	0
000301C	2.03	0.70	0.09	050315	1.949	...	...
000418	1.118	0.75	0.96	050319	3.24	...	...
000911	1.058	0.724 (0.006)	0.39	050401	2.90	...	...
000926	2.066	1.00 (0.18)	0.18 (0.06)	050408	1.24	...	...
010222	1.477	1.07 (0.09)	0	050502	3.793	...	...
011121[a]	0.36	0.80 (0.15)	0	050525	0.606	0.97 (0.10)	0.25 (0.16)
011211	2.14	0.56 (0.19)	0.08 (0.08)	050603	2.821	...	...
020124	3.198	0.91 (0.14)	0	050730	3.97	...	...
020405	0.69	1.43 (0.08)	0	050820	2.615	...	...

Note.—Uncertainties $\Delta\beta$ and $\Delta A_{V,\mathrm{host}}$ are listed in parentheses. Table 1 is published will full references to the observational data in the electronic version of the *Astrophysical Journal*.
[a] Member of the low optical luminosity group; the separation is at $L_{R,1\mathrm{d}} \sim 1.4 \times 10^{45}$ ergs s^{-1} (see Fig. 2).

in the host galaxy extinction at the cosmic rest-frame wavelength $\lambda_{R'} = \lambda_R/(1+z)$, and $\Delta\beta \log(1+z)$ is the error in 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 among the optically bright GRBs there exist two well-separated subcategories. The majority of the bursts (~75%) make up an optically luminous GRB group, which includes well-studied GRBs such as 030329, 990123, and 990510. It is interesting that although the isotropic gamma-ray energies ($E_{\gamma,\mathrm{iso}}$) of GRB 990123 and GRB 030329 differ by almost 2 orders of magnitude, their late optical afterglow luminosities are similar.[5] The other ~25% of the GRBs in our sample constitute the dim group, with the representative bursts being GRBs 021211 and 041006. We zoom in on these light curves in the temporal regime from 0.1 to 10 days in the inset of Figure 1. The bimodal light-curve trajectories during this period are more clearly visible. Based on the separation of the two groups by the luminosity at 1 day [$\log L_{R,1\mathrm{d}}$(ergs cm^{-2}) $= 45.15$; see Fig. 2] and adopting a typical temporal decay index of -1.2, we draw a dividing line for the two groups as $\log L_R = 45.15 - 1.2 \log t'$ (Fig. 1, *dashed line*). It is found that 25 (out of 34) and seven (out of 10) light curves in the luminous and dim groups, respectively, cover this time regime and do not cross the dividing line. They are the most representative (with the smallest scatter) ones in each group. The bursts in the luminous group are typically brighter than those in the dim group by a factor of ~30.

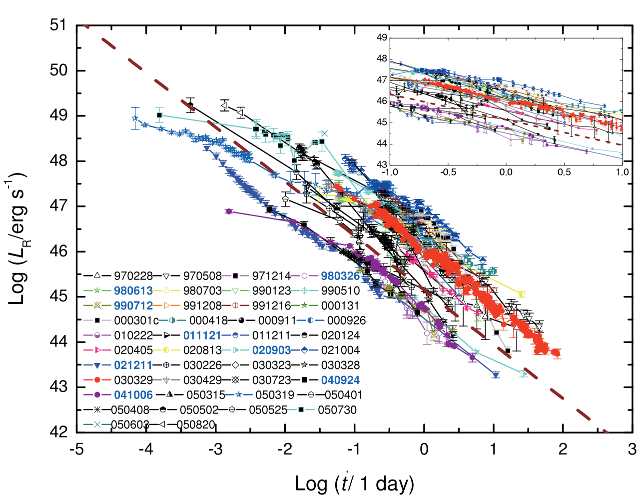

Fig. 1.—The R-band light curves [$L_R(t')$ vs. t'] in the cosmic proper rest frame. The dashed line is a division of the two groups of GRBs, $\log L_R = 45.15 - 1.2 \log t'$. The inset zooms in on the light curves in the time regime from 0.1 to 10 days. Those bursts marked in blue in the key belong to the dim group.

We read off or extrapolate/interpolate the luminosity at a given epoch from the light curves and perform rigorous statistical tests to assess the bimodality of our sample. We first select the intrinsic luminosity at 1 day for our purpose. Our consideration is twofold. 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 two-

[5] We note that Nardini et al. (2006) independently obtained the same result while this Letter was being reviewed.

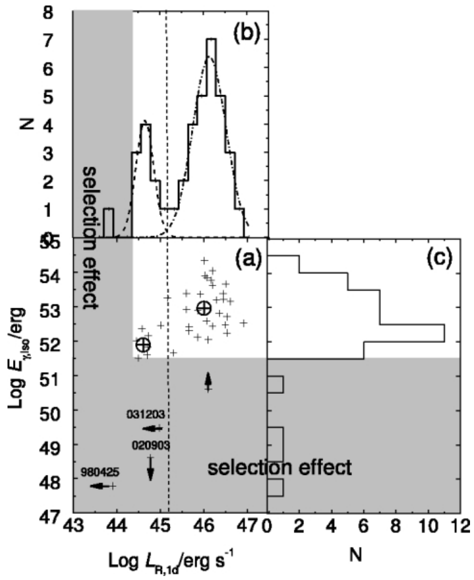

FIG. 2.—(*a*) Two-dimensional distribution of $L_{R,1d}$ and $E_{\gamma,iso}$ and (*b*, *c*) distributions of both quantities for the bursts in our sample. The significant outliers, GRBs 030226, 970508, and 050408, have been excluded. The $E_{\gamma,iso}$ has been corrected to the bandpass 20–2000 keV in the rest frame according to the spectral parameters of prompt gamma-ray emission. The circled plus signs are the means of the two quantities for the two groups (excluding those bursts that only have limits). The gray area marks the parameter region in which the flux threshold selection effect plays a dominant role. The dashed curves in (*b*) are the best fit using a two-Gaussian model. The vertical dashed line is the separation between the dim and the luminous groups in the two-Gaussian model.

dimensional distribution of the intrinsic *R*-band luminosity at 1 day,[6] $L_{R,1d}$, versus $E_{\gamma,iso}$ (Fig. 2*a*), and the distributions of the two quantities, respectively (Figs. 2*b* and 2*c*). Flux thresholds in both the gamma-ray and the optical bands introduce selection effects against low-energy, low-luminosity bursts, and these are indicated by the gray regions in Figure 2. There are three prominent outliers whose light curves deviate from the universal light curves, GRBs 970508, 030226, and 050408. They are excluded in the statistical analyses (see § 4 for a more detailed discussion). While the $E_{\gamma,iso}$ distribution displays a power law with a 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 $\log L_{c,1}(\text{ergs s}^{-1}) = 44.66$ with $\sigma_1 = 0.41$ and $\log L_{c,2}(\text{ergs s}^{-1}) = 46.15$ with $\sigma_2 = 0.77$. The bimodality is at a confidence level of 3 σ, as 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 $\log L_{c,1}(\text{ergs s}^{-1}) = 44.72^{+0.36}_{-0.36}$, $\log L_{c,2}(\text{ergs s}^{-1}) = 46.15^{+0.14}_{-0.20}$, and $c = 0.11^{+0.16}_{-0.06}$ at the 3 σ significance level. These results indicate that the bimodality is not due to statistical fluctuations.

To further examine the bimodality of the distribution at different epochs, we also derived the distributions at $\log t'$(days) of -0.5 and 0.5. We find that the distribution of the luminosities at $\log t'(\text{days}) = 0.5$ is bimodal at the 3 σ significance level. The bimodality of the luminosity distribution at $\log t'(\text{days}) = -0.5$ has a lower (i.e., 2 σ) statistical significance. Nonetheless, the distribution still stands, with a gap at $\log L_R(\text{ergs s}^{-1}) = 45.5$. The lower significance is expected, because of the various factors (reverse shock, early injection, etc.) concerning the early afterglows.

[6] 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 upper limits on their luminosities at 1 day, both yielding $\sim 7 \times 10^{43}$ ergs s^{-1}. Corrected for Galactic extinction, the luminosities are 8.3×10^{43} ergs s^{-1} for GRB 980425 and 9.2×10^{44} ergs s^{-1} for GRB 031203.

4. CONCLUSIONS AND DISCUSSION

We have derived the intrinsic *R*-band afterglow light curves within the cosmic proper rest frame with a complete sample observed from 1997 February 1997 to 2005 August. These light curves follow two apparent universal tracks after 2 hours following the GRB trigger. The optical luminosity at 1 day clearly shows a bimodal distribution, with the peak luminosities being 1.4×10^{46} ergs s^{-1} for the luminous group and 5.3×10^{44} ergs s^{-1} for the dim group.

One interesting feature of the dim group is that these bursts all appear to be at 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 for GRB 980613 ($z = 1.096$) and GRB 021211 ($z = 1.006$), the other bursts in the dim group all have $z < 1$. Besides this 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 light curves. All the bursts in the dim group have a single gamma-ray pulse except for GRB 990712, which has two well-separated pulses. We note that the observed *R*-band magnitudes for the dim GRBs are generally ∼21–22.5 mag a few days after the trigger. Although a burst with $\log L_R(\text{ergs s}^{-1}) = 44.72$ (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 of detecting optical transients fainter than $R \sim 21$ is dramatically reduced. Observational bias as the source of the deficit of high-redshift, optically dim GRBs thus cannot be ruled out.

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 & Draine 2000; Fruchter et al. 2001). It is found that the optical extinctions are 10–100 times smaller than what would be expected from the X-ray absorption (Galama & Wijers 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 cannot be interpreted as a manifestation of the extinction effect. Our results then suggest that there might be two types of progenitor or two types of explosion mechanism in operation.

Some GRBs show an initial shallow decay before landing on the luminous branch. GRB 970508 is the most prominent of these. The light curve is initially almost flat before rebrightening 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. 2006). GRBs 050408 and 050319 exhibit 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 outlier is 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 to an early jet break, with the rapid decay due to the sideways expansion of the jet, which significantly reduces the optical luminosity (Rhoads 1999).

The two apparent universal light-curve tracks at later times are intriguing. It is widely believed that afterglows are synchrotron emission from the 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., $t' = 1$ day), the optical luminosity $L_{R,1\mathrm{d}} \propto E_{k,\mathrm{iso}}^{(p+2)/4}\epsilon_e^{p-1}\epsilon_B^{(p-2)/4}$, where $E_{k,\mathrm{iso}}$ is the isotropic kinetic energy of the fireball, ϵ_e and ϵ_B are shock energy equipartition factors for electrons and magnetic fields, respectively, and p is the electron spectral index. We can see that $L_{R,1\mathrm{d}}$ is independent of the density of the medium and only weakly depends on ϵ_B. The universal afterglow luminosity therefore suggests that both $E_{k,\mathrm{iso}}$ and ϵ_e are uniform values around 1 day for each subclass. A uniform ϵ_e suggests universal properties of relativistic shocks. A uniform $E_{k,\mathrm{iso}}$, on the other hand, is intriguing, since $E_{\gamma,\mathrm{iso}}$ varies over 4 orders of magnitude among long-duration GRBs, and they generally follow a power-law distribution with a cutoff at the low-luminosity end (Schmidt 2001; Norris 2002). They become uniform only when jet beaming corrections are taken into account (Frail et al. 2001). Our results are consistent with the picture in which GRBs with a higher $E_{\gamma,\mathrm{iso}}$ tend to have a higher gamma-ray emission efficiency (Lloyd-Ronning et al. 2004). The $E_{k,\mathrm{iso}}$ derived using 10 hr X-ray data requires a jet beaming correction to achieve a uniform 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 in $E_{k,\mathrm{iso}}$ at early times (Chincarini et al. 2005). Our results therefore suggest a possible evolution of $E_{k,\mathrm{iso}}$ 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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