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THE OPTICAL LUMINOSITY FUNCTION OF GAMMA-RAY BURSTS DEDUCED FROM ROTSE-III OBSERVATIONS

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\textit{Received 2014 January 20; accepted 2014 September 12; published 2014 October 16}

ABSTRACT

We present the optical luminosity function (LF) of gamma-ray bursts (GRBs) estimated from a uniform sample of 58 GRBs from observations with the Robotic Optical Transient Search Experiment III (ROTSE-III). Our GRB sample is divided into two sub-samples: detected afterglows (18 GRBs) and those with upper limits (40 GRBs). We derive $R$-band fluxes for these two sub-samples 100 s after the onset of the burst. The optical LFs at 100 s are fitted by assuming that the co-moving GRB rate traces the star formation rate. While fitting the optical LFs using Monte Carlo simulations, we take into account the detection function of ROTSE-III. We find that the cumulative distribution of optical emission at 100 s is well described by an exponential rise and power-law decay, a broken power law, and Schechter LFs. A single power-law (SPL) LF, on the other hand, is ruled out with high confidence.

\textit{Key words:} gamma-ray burst: general – methods: statistical

\textit{Online-only material:} color figures

1. INTRODUCTION

Gamma-ray bursts (GRBs) are the most luminous explosions in the universe. Although highly transient, they provide a good laboratory to study astrophysics in extreme conditions. Prompt gamma-ray emission refers to the emission component detected by gamma-ray detectors and is commonly interpreted as emission from internal shocks \citep[e.g.,][]{1994Natur.367..621R,1995Natur.375..608D,1998ApJ...508L..33P,2006ApJ...653L.115P} or internal magnetic energy dissipation processes \citep[e.g.,][]{1992ApJ...395....7U,2006MNRAS.369.1194G,2011ApJ...730L..36Z}. Prompt emission is often followed by an afterglow that is the multi-wavelength radiation from the external shock produced by interactions between the ejecta from the fireball and the ambient medium \citep[see, e.g.,][]{2004ApJ...604..318Z,2013MNRAS.435.3787G}. The identification of the first GRB redshift by \textcite{2000ApJ...540..254M,2002ApJ...565L.111L,2004ApJ...610..682F,2006ApJ...645L..19K,2009MNRAS.393L..43S} revealed the cosmological origin and vast energy release from GRBs, which allows their detection out to extreme distances, e.g., $z \sim 8.2$ \citep{2009ApJ...705..941T,2012Sci...337..791S}, and possibly at redshifts as high as $\sim 9.4$ \citep{2011MNRAS.417.2876C}. However, the transient nature of GRBs means that only a limited number have spectroscopic redshifts. This motivates search into correlations between GRB luminosity and various observable parameters in order to derive pseudo-redshifts for GRB events without spectroscopic redshifts \citep[e.g.,][]{2000ApJ...540..254M,2002ApJ...565L.111L,2004ApJ...610..682F,2006ApJ...645L..19K,2009MNRAS.393L..43S}. There is evidence for potential luminosity evolution in the gamma-ray band \citep{2012Sci...337..791S}, but the luminosity function (LF) is strongly dependent on the instrumental detection function, which complicates the interpretation of the results.

Following the identification of the first optical counterpart of a GRB in 1997 February 28 \citep{1997Natur.385..589V}, many statistical studies of optical afterglow (OA) light curves have been carried out, resulting in our current understanding of the general features of the light curve. \textcite{2009ApJ...697.1548D} compared the cumulative distributions of peak gamma-ray photon fluxes and showed that \textit{Swift} and BATSE samples come from the same parent population of bursts. Morphological studies of light curves based on statistical analyses of large samples indicate that there are several emission components in the optical afterglow \citep[e.g.,][]{2006ApJ...645L..19K,2008ApJ...675..820P,2011ApJ...729.1326K,2010ApJ...712L..30K}. Two universal tracks of the late optical
luminosity light curves have been found (e.g., Nardini et al. 2006, Kann et al. 2006). Kann et al. (2010, 2011) compared the optical light curves of different types of GRBs in the pre-
Swift and Swift eras to study the distribution of early luminosities at 43.2 s in the bursts’ rest frame with known redshifts and host-galaxy extinctions. They found that the luminosity distribution can be approximated by three Gaussians. The typical features of GRB OA light curves comprise an early bump and plateau components (Panaitescu & Vestrand 2008, 2011; Li et al. 2012; Liang et al. 2013; Wang et al. 2013). Wang et al. (2013) found that a single power law provides a good description of the LF at 10^3 s. Most of the optical data for these studies, however, were collected from inhomogeneous observations with different instruments. Another issue is that optical observations often only start after the end of prompt gamma-ray emission. The optical LF of GRB afterglows is therefore poorly known since no complete sample within a given threshold is available. The detection of an optical counterpart of a GRB depends on the instrument, exposure time, observation epoch, etc. Therefore, a homogeneous data set from a single instrument, e.g., the Robotic Optical Transient Search Experiment III (ROTEX-III) in this work, can reduce these uncertainties. An analysis of early (e.g., at 100 s) and homogeneous data after the onset of the burst is desirable to facilitate the interpretation of the optical LF of GRBs.

Although the Swift satellite has led to an increase in the number of GRBs with good redshift determinations, the sample is still not sufficiently large to directly measure the LF and is affected by various biases. Since long GRBs are associated with the deaths of massive stars, the assumption that the GRB rate is still not sufficiently large to directly measure the LF and is affected by various biases. Since long GRBs are associated with the deaths of massive stars, the assumption that the GRB rate is affected by various biases. Since long GRBs are associated with the deaths of massive stars, the assumption that the GRB rate is affected by various biases. Since long GRBs are associated with the deaths of massive stars, the assumption that the GRB rate is affected by various biases. Since long GRBs are associated with the deaths of massive stars, the assumption that the GRB rate is affected by various biases. Since long GRBs are associated with the deaths of massive stars, the assumption that the GRB rate is affected by various biases. Since long GRBs are associated with the deaths of massive stars, the assumption that the GRB rate is affected by various biases. Since long GRBs are associated with the deaths of massive stars, the assumption that the GRB rate is affected by various biases. Since long GRBs are associated with the deaths of massive stars, the assumption that the GRB rate is affected by various biases. 

Our final sample consists of 58 GRBs with 18 detections and 40 upper limit measurements. Some of the detections have been published previously (Yost et al., 2007a, 2007b; Rykoff et al. 2009; Yuan et al. 2008; Yuan 2010). For unpublished data, we use the ROTSE-III photometry package (RPHOT; Rykoff et al. 2009) to perform PSF photometry. Since all the ROTSE-III observations were taken unfiltered and the response of the instrument is approximately in the RC band (Rykoff et al. 2009), we adopt RC as our bandpass for photometry.

We take into account and make corrections for extinction in both our Galaxy and the GRB host galaxy. We correct for Galactic extinction (A_V) using the values given by Schlafly & Finkbeiner (2011) as listed in Table 1. We transform the value of A_V to A_R by applying an average extinction law (Cardelli et al. 1989). GRB 110625A is located in a region with very high extinction, A_V = 30.29 (Schlafly & Finkbeiner 2011), making it difficult to place any constraints on the LF based on this burst, which was therefore excluded from our non-detection sample. We adopt a mean value of A_V = 0.2 (Kann et al. 2010) for the host galaxy extinction. We did not consider the uncertainties involved in assuming a mean A_V, including the effects of redshift and the change of attenuation law, since it is difficult to quantify the exact values of these effects. Finally, we corrected the flux from the observer frame to the cosmological rest frame using F(ν, t) = κ F_0(ν, t), where F_0(ν, t) is the flux in the observer frame. The parameter κ is defined by κ = (1 + z)^β_o - α_o - 1 (with the convention F(ν, t) = ν^β_o - α_o), where we adopted the spectral index β_o = 0.75 and power-law index α_o = 1 for the light curves of the optical afterglows. We list the basic properties of the GRBs, namely, the start and end observed time (t_start & t_end), coordinates (R.A. & Dec), Galactic extinction A_V, and the observed flux F_0 of the GRBs in our samples comprising 18 detections and 40 upper limits, in Table 1.

2. OBSERVATIONAL DATA AND METHODOLOGY

ROTEX-III is a network of four identical 0.45 m telescopes distributed around the world to promptly observe OA of GRBs (Akerlof et al. 2003). We use a sample of ROTSE-III data to derive the GRB optical LF. The observed GRB OA rate is assumed to be a convolution of the optical LF with the cosmic GRB rate history. Since the intrinsic LF shape is affected by instrumental sensitivity, we use simulations to determine this effect.

2.1. ROTSE-III Observations

We selected our sample of GRBs from ROTSE-III observations between 2005 February and 2011 July. For uniformity, we defined an epoch for brightness measurement to be 100 s after the burst (with an equivalent exposure time of 5 s). A non-detection, namely, a 3σ upper limit measurement, is also considered if it meets the following two criteria. First, we only consider GRBs that were triggered by the Swift satellite in order to have a uniform solid angle of sky coverage (see Section 2.2 below). Second, the GRB must have ROTSE-III observations both before and after 100 s, thereby allowing an interpolation to 100 s. We have not included GRB 080319B, the naked-eye GRB, which was observed under inclement conditions with CCD condensation (Swan et al. 2008). For upper limit measurements, we used a transformation factor to allow for different exposure times. Since most of the upper limit measurements were obtained with an exposure of 5 s, we normalized all the longer exposure times (either 20 s or 60 s) to 5 s exposures. Some GRBs have optical detections in exposures longer than 5 s, but their observed magnitudes are fainter than the equivalent 5 s limiting magnitude of the instrument (e.g., GRB050401; 8 GRBs in total, which are marked with stars in Table 1). These bursts are considered to be non-detections for the purpose of optical LF construction.

The observed rate of GRB OAs with peak fluxes between F_1 and F_2 is 

\[
\frac{dN}{dt}(F_1 < F < F_2) = \int_{0}^{\Delta z} \int_{L}^{L(F_2,z)} \Phi(L) \times \frac{R_{GRB}(z) \Delta \Omega dV(z)}{4\pi \Delta z} dLdz, \quad (1)
\]
where the factor $(1 + z)^{-1}$ is a result of cosmological time dilation, the parameter $\Delta \Omega = 1.4$ sr is the solid angle covered on the sky by Swift (Salvaterra & Chicarini 2007; we only consider GRBs that are triggered by Swift), and $dV(z)/dz$ is the comoving volume element. The comoving GRB formation rate is assumed to trace the cosmic SFR as

$$R_{\text{GRB}}(z) = k R_{\text{SFR}}(z),$$

(2)

where the factor $k$ is a constant. The SFR, $R_{\text{SFR}}(z)$, in units of $M_\odot \text{Mpc}^{-3} \text{yr}^{-1}$, is parameterized following Hopkins & Beacom (2006) as

$$\log R_{\text{SFR}}(z) = a + b \log(1 + z),$$

(3)

with

$$a = \begin{cases} (-1.70, 3.30), & z < 0.993 \\ (-0.727, 0.0549), & 0.993 < z < 3.80 \\ (2.35, -4.46), & z > 3.80. \end{cases}$$

The maximum redshift $z_{\text{max}}$ is determined by the Lyman $\alpha$ absorption of the emission in the $R$ band.

In this work, we compare the beaming-convolved LF of GRBs $\Phi(L)$ with four model functions:

1. a single power law (SPL):

$$\Phi(L) = \frac{1}{L_\star} \left( \frac{L}{L_\star} \right)^{\alpha_L};$$

(5)

2. a broken power law (BPL):

$$\Phi(L) = \frac{1}{L_\star} \left[ \left( \frac{L}{L_1} \right)^{\alpha_{L1}} + \left( \frac{L}{L_2} \right)^{\alpha_{L2}} \right]^{-1};$$

(6)

3. an exponential rise and power-law decay function (ERPLD):

$$\Phi(L) = \frac{1}{L_\star} \left( \frac{L}{L_\star} \right)^{\alpha_L} \exp \left( -\frac{L}{L_\star} \right);$$

(7)

and a Schechter function:

$$\Phi(L) = \frac{1}{L_\star} \left( \frac{L}{L_\star} \right)^{\alpha_L} \exp \left( -\frac{L}{L_\star} \right),$$

(8)

where $\alpha_L$ and $L_\star$ are parameters determined by fitting the observational data.

The observed rate of GRB OAs is governed by the LF $\Phi(L)$ and the GRB formation rate $R_{\text{GRB}}(z)$ based on fitted parameters including the factor $k, \alpha_L$, and $L_\star$. The constant $k$ can be removed by normalizing the cumulative flux distribution of GRBs to $N(F_{\text{min}}, F_{\text{max}})$ as

$$N(< F) = \frac{N(F_{\text{min}}, F)}{N(F_{\text{min}}, F_{\text{max}})}.$$  

(9)

We search for the best model parameters by evaluating the consistency between the cumulative flux distribution of the observed and expected GRBs with the one-sample Kolmogorov–Smirnov (K-S) test. In this test, the maximum value of the absolute difference between two cumulative distribution functions, D-stat, is evaluated with a significance level Prob. A larger value of Prob indicates better consistency. A value of Prob > 0.1 is generally acceptable to claim statistical consistency, while a value of Prob < $10^{-4}$ rejects the hypothesis of consistency with high confidence.

### Table 1

<table>
<thead>
<tr>
<th>GRB</th>
<th>$t_{\text{start}}$</th>
<th>$t_{\text{end}}$</th>
<th>R.A.</th>
<th>Decl.</th>
<th>$A_v$</th>
<th>$F_{\text{obs}}$</th>
<th>Properties of the ROTSE-III GRB Sample at 100 s After Trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(s)</td>
<td>(s)</td>
<td>(J2000)</td>
<td>(J2000)</td>
<td>(mag)</td>
<td>(erg cm$^{-2}$ s$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>------------------</td>
<td>-----------------</td>
<td>------</td>
<td>-------</td>
<td>------</td>
<td>---------------</td>
<td>-------------------------------------------------------------</td>
</tr>
<tr>
<td>050215A</td>
<td>65.2</td>
<td>200.2</td>
<td>23:13:36.7</td>
<td>49:19:40.8</td>
<td>0.591</td>
<td>6.57</td>
<td></td>
</tr>
<tr>
<td>050306</td>
<td>68.4</td>
<td>185.4</td>
<td>18:49:14.2</td>
<td>09:09:07.2</td>
<td>1.855</td>
<td>38.68</td>
<td></td>
</tr>
<tr>
<td>050401*</td>
<td>33.2</td>
<td>281.2</td>
<td>16:31:29.5</td>
<td>02:11:06.0</td>
<td>0.177</td>
<td>6.32</td>
<td></td>
</tr>
<tr>
<td>050822</td>
<td>31.8</td>
<td>100.0</td>
<td>03:24:25.4</td>
<td>06:41:00.0</td>
<td>0.041</td>
<td>8.75</td>
<td></td>
</tr>
<tr>
<td>051001</td>
<td>85.7</td>
<td>191.9</td>
<td>23:25:36.2</td>
<td>31:30:54.0</td>
<td>0.041</td>
<td>4.59</td>
<td></td>
</tr>
<tr>
<td>06110*</td>
<td>27.0</td>
<td>400.0</td>
<td>01:40:56.9</td>
<td>28:25:40.8</td>
<td>1.696</td>
<td>29.10</td>
<td></td>
</tr>
<tr>
<td>06111B*</td>
<td>32.8</td>
<td>728.6</td>
<td>19:05:49.4</td>
<td>70:22:08.8</td>
<td>0.297</td>
<td>12.95</td>
<td></td>
</tr>
<tr>
<td>06116</td>
<td>79.0</td>
<td>2993.2</td>
<td>05:38:47.5</td>
<td>05:26:16.8</td>
<td>0.697</td>
<td>7.66</td>
<td></td>
</tr>
<tr>
<td>061614</td>
<td>26.8</td>
<td>189.2</td>
<td>21:23:30.5</td>
<td>53:01:37.2</td>
<td>0.058</td>
<td>8.88</td>
<td></td>
</tr>
<tr>
<td>06190B*</td>
<td>19.3</td>
<td>6608.3</td>
<td>03:52:52.0</td>
<td>00:43:44.4</td>
<td>0.472</td>
<td>8.73</td>
<td></td>
</tr>
</tbody>
</table>

Note. These bursts were moved to the upper limit sample from the detected sample based on the 5 s limiting magnitude of the instrument.
2.3. ROTSE-III Sensitivity Function

In order to correct our observed LF for instrumental effects, we performed a simulation based on the number count distribution of the 40 GRBs in our upper limit sample to reconstruct the detection function (i.e., the sensitivity function) of ROTSE-III. The simulation is a four-step process that functions as follows. First, we construct a histogram of the flux limit from the 40 GRB limits. Second, a smoothed broken power-law (SBPL) is used to fit this histogram in the observed flux interval,

\[ N = N_0 \left[ \left( \frac{f}{f_b} \right)^{-\alpha_1} + \left( \frac{f}{f_b} \right)^{-\alpha_2} \right]^{-1/\omega}, \]

where the parameter \( N_0 \) is a normalization factor, the parameter \( f_b \) is the flux at the break point of the SBPL, the parameters \( \alpha_1 \) and \( \alpha_2 \) are two power-law indices, and the parameter \( \omega \) describes the sharpness of the break. The larger the value of the parameter \( \omega \), the sharper the break in the SBPL function. Third, we perform a Monte Carlo simulation \((n = 1000)\) based on the best-fitting SBPL function. The cumulative distribution of the simulated magnitude limits approximates the actual detection function of the instrument. Finally, the model fitting for this cumulative distribution is applied to find the intrinsic LF of the upper limit sample. A similar simulation for the 18 GRBs in the detected sample is used to reconstruct the detected magnitude distribution. Combining the simulations of the limit and detected sub-samples, a simulated “combined” sample is then applied to constrain the LF obtained from ROTSE-III.

3. RESULTS

Figure 1 shows the results of fitting the SBPL function to the simulation histograms for 40 limiting magnitudes (left panel) and 18 detected magnitudes (right panel) with red solid curves. The stepped lines are the Monte Carlo simulations in this figure. The best-fitting parameters, including the normalization factor \( N_0 \), the magnitude \( f_b \) at the break point, the sharpness factor \( \omega \), and the power-law indices \( \alpha_1 \) and \( \alpha_2 \) of SBPL, as described in Equation (10), are presented in Table 2.

The best-fitting SBPL function of the detected and limit sub-samples highlights the necessity to consider the detection function in the study of the GRB optical LF.

Figure 2 shows the cumulative distributions of the afterglows fluxes observed by ROTSE-III (solid circles with Poisson error bars in the left panel) and simulated results (stepped line). The predictions of the flux distribution from the GRB formation rate based on SFR and different LFs are drawn with solid and dashed lines in this figure. The optical LFs with different models (SPL, BPL, ERPLD, and Schechter function) are shown with different colors in the figure. The best-fitting parameters for the models, as well as the results of the K-S test (D-stat, and significance level Prob) are shown with different lines in this figure. The optical LFs with different models (SPL, BPL, ERPLD, and Schechter function) are shown with different colors in the figure. The best-fitting parameters for the models, as well as the results of the K-S test (D-stat, and significance level Prob) are shown with different lines in this figure.

Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( N_0 )</th>
<th>( m_b )</th>
<th>( \alpha_1 )</th>
<th>( \alpha_2 )</th>
<th>( \omega )</th>
<th>Prob</th>
<th>D-stat</th>
</tr>
</thead>
<tbody>
<tr>
<td>detected</td>
<td>0.99</td>
<td>11.31</td>
<td>-20.76</td>
<td>41.86</td>
<td>5.84</td>
<td>0.09</td>
<td>0.28</td>
</tr>
<tr>
<td>limit</td>
<td>0.99</td>
<td>11.06</td>
<td>-11.72</td>
<td>18.67</td>
<td>47.27</td>
<td>0.12</td>
<td>0.19</td>
</tr>
</tbody>
</table>

obtained with ROTSE-III are from the same population as the simulations, is tested using a K-S test. The maximum distance between the cumulative probability functions of the two groups is \( D = 0.28, 0.19 \) with significance levels Prob = 0.09, 0.12, respectively. This indicates that one cannot reject the null hypothesis (a common origin of the two samples) at the 5% significance level, which provides confidence that the simulation based on the best fittings is appropriate in the case that the number of data points may not be large enough to construct the detection function of the instrument. The difference between the detection and limit sub-samples highlights the necessity to consider the detection function in the study of the GRB optical LF.

From Table 3, we find that the values of D-stat are smaller for the “combined (simulated)” sample (including 1000 detection simulations and 1000 upper limit simulations) than those for
the other two samples, including the “obs” data observed by ROTSE-III, and the “limit (simulated)” sample including 1000 detection simulations and 1000 limit simulations. The solid circles with errors labeled in the left panel as “observed” are the afterglows observed by ROTSE-III. The stepped lines are those from simulations. The type of LF is identified by color as described in the text. (A color version of this figure is available in the online journal.)

Figure 2. Model fitting results for the cumulative distributions of 58 afterglows observed by ROTSE-III (left panel), simulated sensitivity function (middle panel), and the “combined (simulated)” sample including 1000 detection simulations and 1000 limit simulations. The solid circles with errors labeled in the left panel as “observed” are the afterglows observed by ROTSE-III. The stepped lines are those from simulations. The type of LF is identified by color as described in the text.

Table 3

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameter</th>
<th>Obs</th>
<th>Limit (Simulated)</th>
<th>Combined (Simulated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPL</td>
<td>(\alpha_L)</td>
<td>(-1.3)</td>
<td>(-1.0)</td>
<td>(-1.0)</td>
</tr>
<tr>
<td></td>
<td>(L_\ast (10^{46} \text{ erg s}^{-1}))</td>
<td>25</td>
<td>34</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>D-stat</td>
<td>0.26</td>
<td>0.40</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>Prob</td>
<td>(1.4 \times 10^{-3})</td>
<td>(1.1 \times 10^{-9})</td>
<td>(2.7 \times 10^{-13})</td>
</tr>
<tr>
<td>BPL</td>
<td>(\alpha_{L1})</td>
<td>26.0</td>
<td>14</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>(\alpha_{L2})</td>
<td>0.05</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>(L_\ast (10^{46} \text{ erg s}^{-1}))</td>
<td>14</td>
<td>0.9</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>D-stat</td>
<td>0.11</td>
<td>0.12</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>Prob</td>
<td>0.52</td>
<td>0.06</td>
<td>0.20</td>
</tr>
<tr>
<td>ERPLD</td>
<td>(\alpha_L)</td>
<td>4.9</td>
<td>0.01</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>(L_\ast (10^{46} \text{ erg s}^{-1}))</td>
<td>1</td>
<td>17</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>D-stat</td>
<td>0.12</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>Prob</td>
<td>0.72</td>
<td>0.05</td>
<td>0.25</td>
</tr>
<tr>
<td>Schechter</td>
<td>(\alpha_L)</td>
<td>(-4.6)</td>
<td>(-3.2)</td>
<td>(-1.6)</td>
</tr>
<tr>
<td></td>
<td>(L_\ast (10^{46} \text{ erg s}^{-1}))</td>
<td>20</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>D-stat</td>
<td>0.10</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>Prob</td>
<td>0.63</td>
<td>0.05</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Notes. One simulation is for the upper limit sample (detection function). The other is for the “combined (simulated)” sample including 1000 detection simulations and 1000 upper limit simulations. The model functions are SPL, BPL, ERPLD, and Schechter function.

The values from these best fits are not all strongly constrained, e.g., the fits are insensitive to values of \(L_\ast\) from 2 to 32 for the “combined (simulated)” sample.

4. DISCUSSION AND CONCLUSIONS

We construct the optical LFs of GRBs at 100 s after the burst onset and study their functional form. The sensitivity function of the instrument is carefully considered with simulations and we find it is necessary to take it into account for the study of the LFs of GRBs. We have found that an ERPLDs, BPLs, or Schechter functions are suitable models for the optical LF of GRBs observed by ROTSE III at 100 s. An SPL functional form is excluded as the optical LF based on our GRB sample with high confidence.

We interpret the parameter \(k\) in our sample as the ratio of GRBs detected by ROTSE-III in the field of view of Swift to all the bursts happening throughout the sky during the Swift observation time. It is, however, difficult to determine the value of \(k\); in the particular case of our study, the K-S test helps eliminate this parameter when finding the best fits by normalizing the cumulative flux distribution of GRBs. An internal shock could produce the emission at the prompt phase and an external shock (reverse shock/forward shock) is thought to be a good candidate for the emission in the afterglow phase. However, the physical reason for the curved LF remains unclear. Kann et al. (2010) interpreted the three Gaussian luminosity distribution as the existence of three “classes” of GRBs. It might be possible that the emission at 100 s in our work originates from internal processes since they are earlier than those from the afterglow phase.

The optical luminosity was found to increase with increasing prompt energy release (Nysewander et al. 2009; Kann et al. 2010), similar to the X-ray luminosity (e.g., Kouveliotou et al. 2004; Liang & Zhang 2006; Amati et al. 2007; Gehrels et al. 2008). The plot of the optical luminosity \(L_{\text{opt}}\) at 100 s after the burst onset versus the isotropic energy \(E_{\text{iso, bol}}\)
radiated during the prompt phase of our sample is studied here to compare with previous work. There does not seem to be any trend of luminosity $L_{\text{opt}}$ to energy $E_{\text{iso, bol}}$ for 58 GRBs reported by ROTSE-III. The black downward pointing triangles are the upper limit reports, and the red squares are optical detections for 18 GRBs.

(A color version of this figure is available in the online journal.)

Figure 3. Plot of optical luminosity $L_{\text{opt}}$ 100 s after triggering vs. the prompt isotropic bolometric energy $E_{\text{iso, bol}}$ for 58 GRBs reported by ROTSE-III. The black downward pointing triangles are the upper limit reports, and the red squares are optical detections for 18 GRBs.

REFERENCES

Swan, H., Yuan, Y., & Rujopakarn, W. 2008, GCN, 7470, 1
Uskov, V. V. 1992, Natur, 357, 472
Zhao, B., & Meszaros, P. 2004, JMPA, 19, 2385

We thank the anonymous referee for very constructive suggestions. We thank Z. G. Dai, B. Zhang, and L. P. Xin for helpful discussions. This work was supported by the National Basic Research Program of China (973 Program, grant No. 2011CB8458800 and 2013CB834900) and the National Natural Science Foundation of China (grant No. 11103026, 11322328, and 11025313). X.F.W. acknowledges support by the One-Hundred-Talents Program, the Youth Innovation Promotion Association, and the Strategic Priority Research Program “The Emergence of Cosmological Structures” (grant No. XDB09000000) of the Chinese Academy of Sciences. The research of J.C.W. is supported in part by NSF grant AST-1109801.