DETERMINING THE DUST EXTINCTION OF GAMMA-RAY BURST HOST GALAXIES: A DIRECT METHOD BASED ON OPTICAL AND X-RAY PHOTOMETRY

Y. Li, Aigen Li, and D. M. Wei

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ABSTRACT

The dust extinction of gamma-ray burst (GRB) host galaxies, which contains important clues to the nature of GRB progenitors and is crucial for dereddening, is still poorly known. Here we propose a straightforward method for determining the extinction of GRB host galaxies by comparing the observed optical spectra to the intrinsic ones extrapolated from the X-ray spectra. The rationale for this method comes from the standard fireball model: if the optical flux decay index equals that of the X-ray flux, then there is no break frequency between the optical and X-ray bands, and therefore we can derive the intrinsic optical flux from the X-ray spectra. We apply this method to three GRBs for which the optical and X-ray fluxes have the same decay indices and to another GRB with an inferred cooling break frequency, and we obtain the rest-frame extinction curves of their host galaxies. The derived extinction curves are “gray” and do not resemble any extinction curves of local galaxies (e.g., the Milky Way, the Small or Large Magellanic Clouds, or nearby starburst galaxies). The amount of extinction is rather large (with a visual extinction of $A_V \sim 1.6–3.4$ mag). We model the derived extinction curves in terms of the silicate-graphite interstellar grain model. As is expected from the gray nature of the derived extinction curve, the dust size distribution is skewed to large grains. We determine, for the first time, the local dust-to-gas ratios of GRB host galaxies by using the model-derived dust parameters and the hydrogen column densities determined from X-ray absorptions.

Subject headings: dust, extinction — gamma rays: bursts

1. INTRODUCTION

It is widely acknowledged that long-duration gamma-ray bursts (GRBs) are associated with the collapse of massive stars (Woosley 1993). Observational evidence supporting this collapsar model includes the underlying supernova components in the afterglows of many GRBs (Zeh et al. 2004) and the observed locations of GRBs in star-forming galaxies and active star-forming regions within their host galaxies (Paczynski 1998; Fruchter et al. 2006). In this scenario, GRBs are born and explode inside dense, dusty environments. The huge gamma-ray energy emission of GRBs is almost unaffected by absorption, which enables us to detect them up to rather high redshifts (e.g., see Tagliaferri et al. 2005). Therefore, the study of the dust and gas properties in the surrounding vicinity of GRBs is of great significance in understanding the interstellar medium (ISM) of star-forming galaxies throughout cosmic history (e.g., see Ramirez-Ruiz et al. 2002). In addition, an accurate apprehension of the dust and gas immediately surrounding GRBs can also help (1) to reveal the nature of so-called dark bursts (i.e., whether the nondetection of an optical afterglow is due to dust extinction or the afterglow is intrinsically dark; see Lazzati et al. 2002 and references therein), (2) to detect the dust evolution with cosmic time, and (3) to correct for the extinction of optical emission in GRB afterglow analysis.

The dust extinction of GRB host galaxies is traditionally modeled using either the Milky Way (MW), the Large Magellanic Cloud (LMC), the Small Magellanic Cloud (SMC), or other presumed extinction curves (e.g., see Straatta et al. 2004; Kann et al. 2006; Tagliaferri et al. 2006; Schady et al. 2007; Starling et al. 2007). Recently, Chen et al. (2006) made the first effort to determine the extinction curves for GRB host galaxies without an a priori assumption of the extinction law. The derived extinction curves differ from any known extinction laws of the Milky Way and external galaxies, challenging the traditional method commonly used in determining the extinction curves of GRB host galaxies.

In this work we propose a novel, straightforward method to determine the extinction of GRB host galaxies by comparing the observed optical spectra to the intrinsic ones extrapolated from the X-ray spectra. That such an analysis is possible follows from the standard fireball model. On the basis of the multiwavelength afterglow photometry (including both the X-ray and optical data), we obtain the extinction curves of four selected bursts. We then model the size distribution and composition of the dust with the silicate-graphite interstellar grain model and obtain the dust-to-gas ratios in the local environments of the GRBs.

2. METHOD

The standard fireball model (Sari et al. 1998), which has been successful in explaining the overall properties of GRB afterglows (Mészáros & Rees 1997), predicts that the afterglow emission is produced by synchrotron radiation of electrons accelerated by the forward shock. In this model, with typical parameters, the optical–to–X-ray spectra can be described by a broken power law with indices of $\beta = (p - 1)/2$ for $\nu < \nu_c$ and $\beta = p/2$ for $\nu > \nu_c$, where $\nu_c$ is the cooling frequency and $p$ is the electron energy distribution index. In most cases, the cooling break position is hard to determine. If the decay indices $\alpha$ of the X-ray and optical bands are different, the cooling frequency lies between them, which makes it difficult for us to calculate the intrinsic optical flux from the X-ray data. However, if the decay indices $\alpha$ of the X-ray and optical bands are the same, then the optical and X-ray bands should lie on the same spectral segment, which makes it possible for us to calculate the intrinsic flux density in any optical band from $F_\lambda = F_X(\lambda/\lambda_X)^{\beta - 2}$, where $\beta$ is the X-ray afterglow flux decay index.
spectral index that we get from fitting the X-ray spectrum and $F_X$ is the X-ray flux density at 1 keV. $t$ is measured from the burst trigger time. $T_{90}$ is the duration of the burst, and $\alpha_o$ and $\alpha_X$ represent the optical and X-ray temporal decay indices, respectively. Data are all taken from the literature, except the values of $\alpha_o$ and $\alpha_X$ for GRB 060729 during the plateau phase, for which we fit its afterglow light curve between $t \sim 0.2$ and 0.6 days to obtain both values.

\[ F_X(\lambda/\lambda_X)^{\beta-2} = A_{\lambda} = 1.086 \ln \frac{1}{F_{\lambda(1+z)}} \tag{1} \]

With an interpolated value of $A_{\lambda}$, we can obtain the extinction curves (normalized to the $I$ band) of the GRB host galaxies.

We then fit the derived extinction curve $A_{\lambda}/A_F$ with the standard silicate-graphite interstellar dust model, which has successfully reproduced the extinction and IR emission of the MW, the SMC, and the LMC (Weingartner & Draine 2001; Li & Draine 2001, 2002). The grain size distribution for both silicates and graphite is modeled with $dN = N(a) da \propto a^{-\gamma} \exp(-a/a_c) da$, where $a$ is the grain radius (assumed to be spherical), ranging from $a_{min} = 0.005$ $\mu$m to $a_{max} = 2.5$ $\mu$m, and $a_c$ is the cutoff size. Note that it is assumed that both silicate dust and graphite dust have the same size distribution. Let $f_{gra}$ be the number fraction of graphitic dust; the mass fraction of graphitic dust is then $f_{gra} = f_{gra} \rho_{gra}/f_{gra} \rho_{gra} + (1 - f_{gra}) \rho_{sil}$, where $\rho_{sil} \approx 3.5$ g cm$^{-3}$ is the mass density of silicate material and $\rho_{gra} \approx 2.24$ g cm$^{-3}$ is that of graphite.

With the fitted dust parameters, we can estimate the dust-to-gas ratio in each of the GRB host galaxies:

\[ \frac{m_{dust}}{m_{gas}} = \frac{M_{gra} + M_{sil}}{1.4 N_H \mu_H}, \tag{2} \]

where $N_H$ is the hydrogen column density in the host galaxy, $\mu_H$ is the atomic weight of H, the factor of 1.4 accounts for helium, and $M_{gra}$ and $M_{sil}$ are the column mass densities of graphitic and silicate material, respectively:

\[ M_{gra} = N_d \int_{a_{min}}^{a_{max}} \frac{4}{3} \pi a^3 N(a) \rho_{gra} f_{gra} da, \tag{3} \]

\[ M_{sil} = N_d \int_{a_{min}}^{a_{max}} \frac{4}{3} \pi a^3 N(a) \rho_{sil} (1 - f_{gra}) da, \tag{4} \]

where $N(a)$ is the normalized dust size distribution. The dust column density $N_d$ can be derived from

\[ A_{\lambda} = 1.086 \int_{a_{min}}^{a_{max}} N(a) \pi a^2 [f_{gra} Q_{ext,gra}(a, \lambda) + (1 - f_{gra}) Q_{ext,sil}(a, \lambda)] d a N_d. \tag{5} \]

### Table 1

**Observational Properties of the Four GRBs**

| GRB       | $z$   | $\beta$ | $F_X$ ($\mu$Jy) | $t$ (days) | $T_{90}$ (s) | $\alpha_o$ | $\alpha_X$ | References |
|-----------|-------|---------|-----------------|------------|-------------|------------|------------|------------|
| 020405.... | 0.691 | 1.0 ± 0.2 | 0.23            | 1.98       | 60          | 1.54 ± 0.06 | 1.97 ± 1.10 | 1, 2       |
| 030227.... | 4     | 0.94 ± 0.05 | 0.125          | 0.87       | 18          | 0.95 ± 0.16 | 0.97 ± 0.07 | 3, 4       |
| 060729.... | 0.54  | 1.06 ± 0.01 | 0.2            | 4.6        | 115         | 1.27 ± 0.10 | 1.29 ± 0.03 | 5          |
| 061126.... | 1.1588 | 0.5 ± 0.07 | 40.5           | 0.023      | 191         | 0.75 ± 0.06 | 1.31 ± 0.01 | 6          |
| 060729*.... | 0.54  | 1.06 ± 0.01 | 3.46           | 0.35       | 115         | 0.26 ± 0.07 | 0.35 ± 0.15 | 5          |

**Notes.**—Here $z$ is the redshift of the burst, $\beta$ is the intrinsic optical/UV to near-IR spectral index derived from the standard afterglow model. $F_X$ is the X-ray flux density at 1 keV, $t$ is measured from the burst trigger time. $T_{90}$ is the duration of the burst, and $\alpha_o$ and $\alpha_X$ represent the optical and X-ray temporal decay indices, respectively. Data are all taken from the literature, except the values of $\alpha_o$ and $\alpha_X$ for GRB 060729 during the plateau phase, for which we fit its afterglow light curve between $t \sim 0.2$ and 0.6 days to obtain both values.

**References.**—(1) Berger et al. 2003; (2) Stratta et al. 2005; (3) Castro-Tirado et al. 2003; (4) Mereghetti et al. 2003; (5) Grupe et al. 2007; (6) Perley et al. 2008.

### Table 2

**Optical/UV to Near-IR Flux Density**

| GRB       | UVW2 | UVM2 | UVW1 | $U$ | $B$ | $V$ | $R$ | $I$ | $J$ | $H$ | $K$ |
|-----------|------|------|------|-----|-----|-----|-----|-----|-----|-----|-----|
| 020405.... | ...  | ...  | ...  | 5.93 | 7.18 | 9.5 | 10.9 | 15.7 | 28.6 | 34.9 | 42.5 |
| 030227.... | ...  | ...  | ...  | 2.4  | 2.7  | ... | ... | ... | 10.2 | 15   |
| 060729.... | 7.56 | 10.18| 11.05| 21.98| 23   | 25.79| ... | ... | ... | ... |
| 061126.... | 65.12| 54.66| 97.41| 120.18| 143.18| 173.6| 217.97| 309.38| 409.42| 523.16|
| 060729*... | 124.2| 170.1| 195.3| 313.1| 359.4| 455.1| ... | ... | ... |

**Notes.**—The flux densities $F_r$ measured in the observer frame are taken at the times of the vertical lines indicated in Fig. 1. All the data have been corrected for Galactic extinction.
decay indices are all taken from the literature, except that of GRB 060729 (around 0.35 days during the plateau phase, for which \(C11\) is not available in the literature), for which we derive the value of \(C11\) by fitting the afterglow light curve between 0.2 and 0.6 days. For GRB 061126, the decay indices of the X-ray and optical bands are different, indicating that the break frequency lies between them. At \(C24\) 30 ks, the \(R\)-band afterglow shows a break (see Fig. 1d) that can be interpreted as the spectral break passing through the \(R\) band, allowing us to calculate the intrinsic optical flux from

\[
F_{\nu}/F_X = (\nu/\nu_X)^{-\beta - 0.5(\nu_X/\nu)^{-\beta}}.
\]

4. RESULTS

We present in Table 3 the derived \(A_k\)-values of the GRB host galaxies at every observed optical band, and in Table 4 we present the \(V\)-band extinction versus the hydrogen column density (\(AV/\hat{N}\)) and the dust-to-gas ratio. Errors in the X-ray spectrum can bring about uncertainties in the extrapolated optical fluxes and thus in the derived value of \(A_k\). We estimate the errors of \(A_k\) from \(\sigma_{A_k}\) (the X-ray spectral index) through equation (1). Larger errors of the X-ray spectrum result in larger uncertainties in \(A_k\) (e.g., see data for GRB 020405 in Table 3 and Fig. 2). Most noticeably, the derived extinction curves of the four bursts are rather “gray” (i.e., with a weak dependence on wavelength; see Fig. 2). Since all these extinction curves have very similar slopes, we put all the extinction data of the four bursts together to fit them to the silicate-graphite grain model. The best-fit parameters are

\[
\begin{align*}
f_{\text{gra}} = 0, \\
\alpha_c &\approx 2.60, \\
\beta &\approx 2.80, \\
\sigma^2 &\approx 0.12,
\end{align*}
\]

which we obtained by summing up all wave bands and all GRBs, where \(\sigma^2\) is the uncertainty for a given GRB at a given band. A prominent feature is the considerably small value of \(\beta\) (the canonical value of \(\beta\) is 3.5), which indicates a grain size distribution that is skewed toward substantially large grains. The main reason that \(f_{\text{gra}} \approx 0\) is the absence of the 2175 Å extinction bump in the derived extinction curves, which is generally attributed to small graphitic grains or PAHs.

5. DISCUSSION

Previous works concerning the dust extinction of GRB host galaxies mostly focused on fitting the observed photometry with the intrinsic power-law spectrum reddened by certain “standard” extinction curves inferred from the Milky Way or nearby galaxies.

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4 We note, however, that this burst, like many other Swift bursts, does not obey the closure relation in the standard afterglow model (Perley et al. 2008), which adds uncertainties to our analysis. But the uncertainty of the break frequency does not appear to affect the shape of the derived extinction curve; as can be seen in Fig. 2, the extinction curve for the other three bursts remains gray even if we ignore the GRB 061126 data.
| GRB       | UVW2 | UVM2 | UVW1 | U   | B   | V   | R   | I   | J   | H   | K   |
|-----------|------|------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 020405....| ...  | ...  | ...  | 2.66 ± 1.12 | 2.65 ± 1.16 | 2.60 ± 1.21 | 2.70 ± 1.26 | 2.58 ± 1.31 | 2.29 ± 1.39 | 2.37 ± 1.45 | 2.47 ± 1.51 |
| 030227....| ...  | ...  | ...  | 2.88 ± 0.26 | ...           | 3.16 ± 0.28 | ...           | ...           | ...           | ...           | 2.58 ± 0.33 | 2.54 ± 0.35 |
| 060729....| 1.91 ± 0.05 | 1.71 ± 0.05 | 1.82 ± 0.05 | 1.41 ± 0.05 | 1.62 ± 0.06 | 1.71 ± 0.06 | ...           | ...           | ...           | ...           | ...           | ...           |
| 061126....| ...  | 4.09 ± 0.03 | 4.38 ± 0.03 | 3.93 ± 0.04 | 3.81 ± 0.04 | 3.74 ± 0.04 | 3.63 ± 0.04 | 3.49 ± 0.04 | 3.34 ± 0.05 | 3.19 ± 0.05 | 3.06 ± 0.05 |
| 060729*   | 2.02 ± 0.05 | 1.79 ± 0.05 | 1.84 ± 0.05 | 1.67 ± 0.05 | 1.78 ± 0.05 | 1.74 ± 0.05 | ...           | ...           | ...           | ...           | ...           | ...           |
X-ray absorption, assuming a solar metal abundance at the same time when the ultraviolet (FUV), often requires a small value of the SMC-type extinction, which, with a steep rise into the far-ultraviolet (UV), is usually ascribed to a lower dust-to-gas ratio in GRB host galaxies (e.g., see Watson et al. 2006). However, there is no obvious reason why the amount of dust is low in the dense environment surrounding GRBs. We note that the dust extinction is very sensitive to the dust size distribution, and for larger grains evaporation of smaller grains due to the intense X-ray and UV radiation up to ~20 pc from the GRB (Waxman & Draine 2000;Fruchter et al. 2001; Savaglio et al. 2003), and (3) preferential destruction of small grains by high-energy ions in fast shocks (Jones 2004). Perna et al. (2003) computed the extinction curve that is obtained if standard Galactic dust is exposed to a GRB lasting more than a few tens of seconds (three of the four bursts in our sample meet this requirement; see Table 1) and found that the extinction curve can be very flat, which is in accordance with our result. We favor the grain growth hypothesis, since the preferential destruction of small grains only occurs in the immediate GRB environment (~10–20 pc from the burst).

It has long been proposed that GRB afterglow radiation, as well as the prompt emission, can destroy dust grains and cause the value of $A_V$ to decrease with time (e.g., see Vreeswijk et al. 1999). We test this effect for GRB 060729, which is exceptionally bright in X-rays, as well as at UV/optical wavelengths, showing an unusually long continuous plateau phase (~1 day). We derive values of $A_V \approx 1.70 \pm 0.20$ mag at $t = 0.35$ days (in the plateau phase) and $A_V \approx 1.59 \pm 0.20$ mag at $t = 4.6$ days (in the normal decay phase, respectively (see Tables 1 and 4), which indicates that there is no significant dust destruction during this time. Detailed studies of dust destruction by GRBs will be presented in a forthcoming paper (Z. Jin et al. 2008, in preparation).

In accordance with previous works, we find that the average value of the ratio $A_V/N_H$ is smaller than that in the Milky Way, which is usually ascribed to a lower dust-to-gas ratio in GRB vicinities (e.g., see Watson et al. 2006). However, there is no obvious reason why the amount of dust is low in the dense environment surrounding GRBs. We note that the dust extinction is very sensitive to the dust size distribution, and for larger grains evaporation of smaller grains due to the intense X-ray and UV radiation up to ~20 pc from the GRB (Waxman & Draine 2000; Fruchter et al. 2001; Savaglio et al. 2003), and (3) preferential destruction of small grains by high-energy ions in fast shocks (Jones 2004). Perna et al. (2003) computed the extinction curve that is obtained if standard Galactic dust is exposed to a GRB lasting more than a few tens of seconds (three of the four bursts in our sample meet this requirement; see $T_{90}$ in Table 1) and found that the extinction curve can be very flat, which is in accordance with our result. We favor the grain growth hypothesis, since the preferential destruction of small grains only occurs in the immediate GRB environment (~10–20 pc from the burst).

The extinction curve derived in our work is flat, almost independent of wavelength, and is even more “gray” than the gray type of extinction curve observed by Chen et al. (2006), similar to the Calzetti et al. (1994) law, which is suitable for local starburst galaxies. This result is in good agreement with other works fitting the SEDs of these bursts (e.g., Stratta et al. 2005; Li et al. 2008). In particular, Perley et al. (2008) found that for GRB 061126 the extinction curve is gray. Gray extinction has also been observed in Galactic dense clouds (Cardelli et al. 1988) and in the circumnuclear region of some AGNs (see Li 2007 for a review). Gray extinction is produced by a dust distribution biased toward large grains (see § 4), which may form from (1) the grain coagulation naturally expected in the dense environment surrounding GRBs (Maiolino et al. 2001a, 2001b), (2) the biased

**TABLE 4**

| GRB     | $A_V$ (mag) | $N_H$ (10$^{22}$ cm$^{-2}$) | $A_V/N_H$ (10$^{-22}$ mag cm$^2$) | $m_{dust}/m_{gas}$ (10$^{-2}$) |
|---------|-------------|-----------------------------|-----------------------------------|-------------------------------|
| 020405..| 2.50 ± 1.17 | 0.8 ± 0.2                   | 3.2 ± 1.6                          | 0.99 ± 0.52                   |
| 030227..| 2.57 ± 0.32 | 6.8$^{+1.6}_{-0.8}$        | 0.38$^{+0.22}_{-0.11}$            | 0.12$^{+0.07}_{-0.05}$        |
| 060729...| 1.59 ± 0.20 | 0.076 ± 0.003               | 20.9 ± 2.8                         | 6.5 ± 0.9                     |
| 061126...| 3.35 ± 0.43 | 1.1 ± 0.3                   | 3.0 ± 0.9                          | 0.94 ± 0.28                   |
| 060729...| 1.70 ± 0.20 | 0.076 ± 0.003               | 22.4 ± 2.8                         | 6.9 ± 0.9                     |

Notes.—Here $A_V$ is the rest-frame V-band extinction of the GRB host galaxies, and $N_H$ is the rest-frame equivalent column density of hydrogen measured from X-ray absorption, assuming a solar metal abundance at the same time when the multiband spectra were taken (see § 2).

**Fig. 2.**—Rest-frame extinction curves (normalized to the V band) for our four GRB host galaxies and the best-fit extinction curve from the silicate-graphite model (thick black line). Also shown are the Milky Way, SMC, and LMC extinction curves.
the extinction (on a per unit mass basis) is low, but the amount of dust may still be high (e.g., see Li 2007). In fact, on the basis of the model fit dust parameters, the dust-to-gas ratios for most bursts are larger than that in the Milky Way. On the other hand, grain growth through coagulation in dense molecular clouds enshrouding GRBs is expected, and this would result in a dust size distribution that was biased in favor of large grains, a flat extinction curve, and a reduced value of $A_V/N_H$.

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