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

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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 (Paczyński 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 Stratta 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 ν_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 α 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 α 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 β is the X-ray afterglow

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TABLE 1

Observational Properties of the Four GRBs

GRB	z	β	F_X (μJy)	t (days)	T_{90} (s)	α_o	α_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*[a]	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, β 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 α_o and α_X represent the optical and X-ray temporal decay indices, respectively. Data are all taken from the literature, except the values of α_o and α_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.

[a] Data are taken during the plateau phase. See § 5 for discussion.

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.

spectral index that we get from fitting the X-ray spectrum and F_X is the X-ray flux density. After correcting for Galactic extinction using the reddening maps of Schlegel et al. (1998), we can describe the observed spectral energy distribution (SED) of a GRB at redshift z as $F_{\lambda(1+z)} = F_\lambda \exp(-A_\lambda/1.086)$. Therefore, the extinction of the GRB host galaxy can be given by

$$A_\lambda = 1.086 \ln \frac{F_X(\lambda/\lambda_X)^{\beta-2}}{F_{\lambda(1+z)}}. \quad (1)$$

With an interpolated value of A_V, we can obtain the extinction curves (normalized to the V band) of the GRB host galaxies.

We then fit the derived extinction curve A_λ/A_V 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 $dn = N(a)\, da \propto a^{-\eta} \exp(-a/a_c)\, da$, where a is the grain radius (assumed to be spherical), ranging from $a_{\rm min} = 0.005\ \mu$m to $a_{\rm max} = 2.5\ \mu$m, and a_c is the cutoff size. Note that it is assumed that both silicate dust and graphitic dust have the same size distribution. Let $f_{\rm gra}$ be the number fraction of graphitic dust; the mass fraction of graphitic dust is then $f'_{\rm gra} = f_{\rm gra}\rho_{\rm gra}/[f_{\rm gra}\rho_{\rm gra} + (1 - f_{\rm gra})\rho_{\rm sil}]$, where $\rho_{\rm sil} \approx 3.5$ g cm^{-3} is the mass density of silicate material and $\rho_{\rm gra} \approx 2.24$ 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:

$$\frac{m_{\rm dust}}{m_{\rm gas}} = \frac{M_{\rm gra} + M_{\rm sil}}{1.4 N_{\rm H} \mu_{\rm H}}, \quad (2)$$

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

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

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

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

$$A_\lambda = 1.086 \int_{a_{\rm min}}^{a_{\rm max}} N(a)\pi a^2 \left[f_{\rm gra} Q_{\rm ext,\,gra}(a,\ \lambda) + (1 - f_{\rm gra}) Q_{\rm ext,\,sil}(a,\ \lambda) \right] da\, N_d, \quad (5)$$

where $Q_{\rm ext,gra}(a,\ \lambda)$ and $Q_{\rm ext,\,sil}(a,\ \lambda)$ are the extinction efficiencies of dust of radius a at wavelength λ for the graphitic and silicate material, respectively.

3. DATA

We select four GRBs that have both optical and X-ray observations. Photometric data are taken from the literature (see Tables 1 and 2). The optical–to–X-ray spectra are extracted when the afterglow light curve is in a steady power-law state (e.g., see Panaitescu & Kumar 2001; Fan & Piran 2006 for detailed analysis) to avoid complex phases (i.e., X-ray flares or rebrightening when the optical and X-ray emissions are probably due to different components [Zhang et al. 2006; Fan & Wei 2005]; see Fig. 1). For GRB 020405, GRB 030227, and GRB 060729, we adopt the spectra obtained when the cooling frequency ν_c falls below the optical band, indicating an intrinsic single power-law spectrum through the optical and X-ray bands as discussed above. The

TABLE 2

Optical/UV to Near-IR Flux Density

GRB	F_ν (μJy)										
	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_ν 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.