DUST PROPERTIES IN THE AFTERGLOW OF GRB 071025 AT z ∼ 5

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Received 2011 July 18; accepted 2011 September 21; published 2011 October 13

ABSTRACT

At high redshift, the universe is so young that core-collapse supernovae (SNe) are suspected to be the dominant source of dust production. However, some observations indicate that the dust production by SNe is an inefficient process, casting doubts on the existence of abundant SNe-dust in the early universe. Recently, Perley et al. reported that the afterglow of GRB 071025—an unusually red gamma-ray burst (GRB) at z ∼ 5—shows evidence for SNe-produced dust. Since this is perhaps the only high-redshift GRB exhibiting compelling evidence for SNe-dust but the result could easily be affected by small systematics in photometry, we re-examined the extinction properties of GRB 071025 using our own optical/near-infrared data at a different epoch. In addition, we tested SNe-dust models with different progenitor masses and dust destruction efficiencies to constrain the dust formation mechanisms. By searching for the best-fit model of the afterglow spectral energy distribution, we confirm the previous claim that the dust in GRB 071025 is most likely to originate from SNe. We also find that the SNe-dust model of 13 or 25 $M_\odot$ without dust destruction fits the extinction property of GRB 071025 best, while pair-instability SNe models with a 170 $M_\odot$ progenitor poorly fit the data. Our results indicate that, at least in some systems at high redshift, SNe with intermediate initial masses within 10–30 $M_\odot$ were the main contributors for the dust enrichment, and the dust destruction effect due to reverse shock was negligible.

Key words: dust, extinction – galaxies: high-redshift – galaxies: ISM – gamma-ray burst: general – gamma-ray burst: individual (GRB 071025)

1. INTRODUCTION

Dust plays an important role in our understanding of galaxy formation and evolution over cosmic history. Dust absorbs and scatters ultraviolet (UV) and optical light from young stars, making it difficult to comprehend how stars were formed in galaxies from optical and near-infrared (NIR) observations that sample the light from young stars re-emitted in the rest-frame ultraviolet (UV) and optical lights of high-redshift objects. Although infrared and submillimeter observations allow us to sample the redshifted UV/optical lights of high-redshift objects, it is imperative to know how the dust extinguishes the UV/optical light at high redshift, in order to understand how stars and galaxies formed in the early universe.

In the local and the intermediate-redshift (z < 3) universe, asymptotic giant branch (AGB) stars are one of the major dust sources (Ferrarotti & Gail 2006). When the universe was much younger (∼1 Gyr) or at z > 5, however, AGB stars could not have been the main producers of dust simply because stars at that epoch did not have enough time to evolve into the AGB phase. It is also known that core-collapse supernovae (SNe) can produce dust grains (Kozasa et al. 1989; Todini & Ferrara 2001; Nozawa et al. 2003). Since core-collapse SNe can occur on short timescales, the dust in the early universe is speculated to have come from SNe (Maiolino et al. 2004). However, dust production from SNe is known to be inefficient (Green et al. 2004; Ercolano et al. 2007; Rho et al. 2009), making it unclear if core-collapse SNe can produce a sufficient amount of dust to significantly obscure star formation activities at high redshift. Observations of broad absorption line quasars at high redshift and some gamma-ray bursts (GRBs) suggest that their rest-frame spectral energy distributions (SEDs) can be best fitted if one assumes an extinction curve dominated by SNe-dust (Maiolino et al. 2004; Hirashita et al. 2005, hereafter H05; Stratta et al. 2007; Gallerani et al. 2010). In such a study, GRBs can be very useful. A GRB afterglow spectrum in UV/optical follows a simple power law that results from the synchrotron radiation of accelerated relativistic electrons in shocks propagating into the surrounding medium of GRB progenitors, making it easy to trace dust extinction curves imprinted on the SEDs. The extreme brightness of GRBs helps us obtain their SEDs at high redshift even with a small telescope. Currently, observational constraints on dust in high-redshift GRBs are weak. While Stratta et al. (2007) claimed that the extinction property of GRB 050904 at z = 6.29 is due to SNe-dust, a reanalysis of GRB 050904 data by Zafar et al. (2010) reveals no strong evidence for SNe-dust. Other high-redshift GRBs are also known to harbor small amounts of dust (Cucchiara et al. 2011; Zafar et al. 2011).

GRB 071025 is an unusually red GRB at a redshift of z ∼ 5 (Im et al. 2007; Perley et al. 2010, hereafter P10). Its red color and the inflexed shape of the afterglow SED suggest extinction dominated by SNe-dust (Perley et al. 2010). Other than GRB 050904, GRB 071025 is currently the only GRB which is claimed to harbor SNe-dust. However, as we saw from the case of GRB 050904, subtle systematic errors in photometry could lead to a large difference in the derived dust extinction properties (Zafar et al. 2010; P10). Therefore, in order to provide an independent assessment of the dust extinction properties of GRB 071025, we analyzed the SED of its afterglow using our own data set of optical/NIR images taken in RIKHs, and constructed at a different epoch from P10. In addition to the verification for SNe-dust, we examined a variety of SNe-dust...
extinction models from H05 and Hirashita et al. (2008, hereafter H08) to constrain the progenitor mass and the importance of the destruction of the dust by shocks.

2. ANALYSIS

2.1. Observation and Data Analysis

We started imaging the afterglow of GRB 071025 using the 1 m telescope at Mt. Lemmon Optical Astronomical Observatory (LOAO) on 2007 October 25, 04:26:54.07 UT, t ∼ 1080 s after the Swift Burst Alert Telescope (BAT) trigger (Pagani et al. 2007). We obtained B-, V-, R-, and I-band imaging data up to the end of October 25 and to a part of October 26 (Im et al. 2007; Lee et al. 2010). Our data showed detections of a bright afterglow in the I and a faint counterpart in the R. The afterglow was not detected in the B and V. We reduced the data using the standard procedures of dark subtraction and flat-fielding using IRAF packages. We obtained the photometry of the afterglow and surrounding stars using SExtractor with the parameters of five pixels for DETECT MINAREA, 1.2σ for DETECT THRESH, and 1.2σ for ANALYSIS THRESH (Bertin & Arnouts 1996). The magnitudes were computed by using circular apertures with an aperture radius of 1.5 FWHM of point-spread functions and 1.2 aperture corrections were derived from bright stars in the field, which amounted to 0.3–0.4 mag. We obtained the data for standard stars (SA95 and SA115) in the second night which were used to carry out the photometry calibration of the GRB 071025 field.

The J-, H-, and Ks-band data were obtained with the simultaneous quad infrared imaging device (SQIID) on the Kitt Peak Mayall 4 m telescope at Steward Observatory, with the start time of 2007 October 25, 05:56:59 UT (Jiang et al. 2007). The total exposure time in each band was 240 s and the three bands’ data were taken at the same time. The photometry was calibrated using Two Micron All Sky Survey point sources brighter than J = 16.0, H = 15.5, and Ks = 14.0 mag within a 120 arcsec distance from the afterglow. Additional J, H, and Ks data were obtained at t ∼ 1.05 days with the Canada–France–Hawaii Telescope.

The results of the photometry are presented in Table 1, where the magnitudes are given in the AB system. For the conversion of the Vega-based magnitudes into AB magnitudes, we used the conversion relation of Frei & Gunn (1994) for the R' bands and Ciliegi et al. (2005) for the JHKs bands. Galactic extinction was also corrected using E(B − V) = 0.07 (Schlegel et al. 1998), which amounts to 0.19, 0.14, 0.06, 0.04, and 0.03 mag in RIJKs, respectively.

2.2. Synchronization of Photometry

Since GRB afterglows change their brightness and in some cases their colors, it is necessary to construct an SED at a given epoch for the analysis of GRB 071025. We adopt the mid-time of the JHKs data (t = 6605 s) as the epoch for which we construct the SED, since the JHKs data were taken simultaneously. Note that we used the form of $F_{\nu,v} \sim t^{-\alpha} v^{-\beta}$ (Sari et al. 1998) to fit the data, where $\nu$ is the observed frequency, $\alpha$ is temporal index, and $\beta$ is spectral index.

Before determining the SED at this epoch, we consider if it is appropriate to consider such an SED as a simple power-law SED from synchrotron radiation by analyzing its temporal evolutions. At $t > 1500$ s, P10 find that the light curves in the X-ray and the optical/NIR are described by simple power laws. By fitting single power-law functions to the light curves of the publicly available Swift’s X-Ray Telescope data5 (Evans et al. 2007) and to the J-, J-, and Ks-band data including those presented in P10, we find that over an interval of $t = 1900$ to 17,000 s, $\alpha_X = 1.75 \pm 0.06$, $\alpha_J = 1.47 \pm 0.06$, $\alpha_I = 1.44 \pm 0.04$, and $\alpha_K = 1.41 \pm 0.03$, or $\alpha_{\text{optical}} - \alpha_X \simeq -0.25$ to $-0.34 \pm 0.08$. When the analysis is extended to $t \sim 10^5$ s, we get $\alpha_J - \alpha_X = -0.27 \pm 0.04$. These results, being consistent with $\alpha_{\text{optical}} - \alpha_X < -0.25$ of a uniform ambient environment (Urata et al. 2007), suggest that the cooling break (v_c) lies between the X-ray and the optical wavelengths and that the light in the optical/NIR is dominated by the afterglow from external shocks. Since we also find no late time prompt signal (e.g., flare and shallow decay) in the X-ray, we conclude that stable afterglow light characterizes the SED at $t = 6605$ s.

The remaining task is to synchronize R- and I-band photometry to this epoch. One of the I-band images from LOAO is nearly

### Table 1

| Filter | Facility | Mid-point Time Elapsed after Swift Alert | Total Integration Time | Magnitude\(^a\)\(^b\) |
|--------|----------|---------------------------------------|------------------------|---------------------|
| I      | LOAO     | 1091 s                                | 30 s                   | 17.33 ± 0.08       |
| I      | LOAO     | 1901 s                                | 300 s                  | 17.27 ± 0.09       |
| I      | LOAO     | 3703 s                                | 300 s                  | 18.46 ± 0.09       |
| I      | LOAO     | 5061 s                                | 300 s                  | 18.81 ± 0.15       |
| I      | LOAO     | 6605 s                                | ...                    | 19.18 ± 0.16       |
| I      | LOAO     | 6814 s                                | 300 s                  | 19.23 ± 0.16       |
| R      | LOAO     | 1563 s                                | 300 s                  | 18.95 ± 0.17       |
| R      | LOAO     | 6605 s                                | ...                    | 21.3 ± 0.30        |
| J      | SQIID    | 6605 s                                | 240 s                  | 18.18 ± 0.05       |
| H      | SQIID    | 6605 s                                | 240 s                  | 17.83 ± 0.06       |
| K      | SQIID    | 6605 s                                | 240 s                  | 17.31 ± 0.05       |
| J      | CFHT     | 90589 s                               | 1200 s                 | 22.13 ± 0.35       |
| H      | CFHT     | 92308 s                               | 1050 s                 | 21.56 ± 0.24       |
| K      | CFHT     | 88792 s                               | 1200 s                 | 20.78 ± 0.12       |

Notes.

\(^a\) The magnitudes are in the AB magnitude system.

\(^b\) Galactic extinction was corrected.

5 http://www.swift.ac.uk/xrt_curves/00295301/
contemporaneous with the JHK\textsubscript{s} data, lagging behind the NIR observation by only 209 s. To correct for the small difference in the observed time, we interpolate the I-band data with the power-law model.

We fit the I-band light curves with our own data only, and with additional I-band data from P10. The fitted values of \( \alpha \) are 1.44 ± 0.11 and 1.47 ± 0.06 without or with the P10 data, respectively. The necessary correction to derive the contemporaneous I-band magnitude from the \( t = 6814 \) s data point is +0.050 mag with \( \alpha = 1.47 \) and +0.049 mag with \( \alpha = 1.44 \). The difference in the correction due to the choice of \( \alpha \) is negligible, hence we adopted the correction of 0.05 mag to compute the I-band magnitude at 6605 s, which gives \( I = 19.18 ± 0.16 \) mag.

For R-band photometry, we used two methods. First, we extrapolated the R-band detection at \( t = 1500 \) s to \( t = 6605 \) s assuming an achromatic decay of the light curve during this period, as found in P10. This gives the R-band photometry of \( R = 21.3 \) mag. For the second approach, we derived a limit in the R-band photometry from a stacked image made of seven 300 s R-band frames around \( t = 6605 \) s. In the stacked image, no afterglow was detected, giving an upper limit in R-band photometry at 21.1 mag at 3\( \sigma \). These two methods give consistent results, therefore we adopt \( R = 21.3 \) mag for the R-band photometry at \( t = 6605 \) s. For the 1\( \sigma \) uncertainties of data, 0.16 mag is used in I band to reflect the uncertainty in \( \alpha \). In the case of R-band, we adopt the error, 0.3 mag, of the R frame at \( t = 1500 \) s.

### 3. ANALYSIS METHOD

The photometry data are fitted using model SEDs as described below. The underlying afterglow emission is assumed to follow a simple power law of \( F_\nu \sim \nu^{-\beta} \) as produced by synchrotron emission of relativistically moving particles. The attenuation of photons below Ly\( \alpha \) is implemented following the prescription of Madau (1995). For the intrinsic dust extinction of GRB 071025, we try the Milky Way (hereafter, MW), Large Magellanic Cloud (LMC), Small Magellanic Cloud (SMC) extinction laws (Pei 1992), and an extinction curve from Calzetti & Kinney (1994).

For SNe-dust extinction curves, we try an empirical extinction curve derived from \( z \approx 6 \) quasars (Maiolino et al. 2004) and theoretical extinction curves of H05 and H08 (see discussion in Section 4.2 for more details of the model). The model SEDs are convoluted with the transmission curves of filters and quantum efficiency of CCD (Lee et al. 2010).

### 4. RESULTS AND DISCUSSION

#### 4.1. Redshift of GRB 071025

We derive the redshift of GRB 071025 before proceeding to a detailed comparison of the best-fit models using different extinction curves. By fixing the redshift, direct comparison between different models becomes more straightforward. Fixing the redshift to a single value can be justified if the derived redshift is not strongly dependent on the models.

In order to determine the redshift, we fit the observed SED with different extinction curves with four free parameters: redshift, \( A_V \), \( \beta \), and the normalization factor. We find that the derived redshifts are all between 4.60 and 4.85\( ±0.05 \) due to the sharp break at \( R \sim 2 \) which can be explained by intergalactic absorption of the light below Ly\( \alpha \), consistent with the value reported in P10. Since the dependence of the redshift on the assumed dust extinction curves is small, we will fix the redshift of GRB 071025 to a fiducial value of 4.8 in the following analysis of the extinction property. We tried the same analysis using different values for the redshift and find that the main conclusion is not affected by the choice of redshift. The differences between the \( \chi^2 \) of best-fit SNe-dust models and less favorable models are always greater than 3 over the plausible redshift range.

#### 4.2. Dust Properties

Figure 1 shows the result of the SED fit with various dust extinction curves (SMC, MW, Calzetti, and Maiolino). As in P10, we observe an inflection in the observed SED shape—as we go from the shorter to the longer wavelength, JHK\textsubscript{s}, data points move up and down with respect to a simple power-law model SED. While the best-fit models with SNe-dust have \( \chi^2 \) values less than 1, models with the dust extinction curves of LMC, SMC, MW, and Calzetti produce the \( \chi^2 \) values of about 4–5. The MW and the LMC extinctions are characterized by a 2175 Å bump which is absent in the SED of GRBs, and the best-fit \( A_V \) values of these models converge to zero. The SED with the Calzetti curve is featureless and similar to the SED with no extinction. Although the adoption of the SMC extinction curve improves the goodness of the fit a little bit compared with the MW or the Calzetti curves, it cannot reproduce the observed changes of slopes between JHK\textsubscript{s} bands as well as the SNe-dust extinction curves.

Since some of the fits converge to no extinction, we tried a fit without dust extinction, which has the benefit of reducing one free parameter. The fit returns the \( \chi^2_{\text{red}} \) of 2.55, an improvement over the fits with the MW and the LMC extinction curves. However, the best-fit spectral slope is too steep at \( \beta = 1.6 \), which we argue as unfavorable below.

Our light curve analysis indicates that the afterglow emission follows the external shock model with \( F(t, \nu) \sim I(t, \nu) \nu^{\beta_X} \) for the optical/NIR, where \( p \) is electron power-law index (Sari et al. 1998). From our optical/NIR light curves, we get \( p \approx 2.97 \) and consequently \( \beta \sim 0.99 \). With the external shock model, \( \beta_X \) should follow \( \beta_X = \beta + 0.5 \sim 2.1 \) if \( \beta \sim 1.6 \), but we find that \( \beta_X \) only is 1.07 ± 0.1 at \( t = 3000–11,000 \) s.\(^6\) Furthermore, GRB afterglows are known to have \( \beta \approx 0.6 \) and \( \beta \lesssim 1.1 \) for all the well-studied cases (Kann et al. 2006, 2010; Zafar et al. 2011).

The SNe-dust models perform far better than those with other dust extinction laws, confirming the previous result from P10.

#### 4.3. Progenitor and Environment of the Dust-producing SNe

H05 and H08 allow us to test various SNe-dust production scenarios with a broad progenitor mass range from 13 to 170 \( M_\odot \), with or without mixing of heavy elements inside the He-shell, and with or without shock destruction of dust. Dust grains can be destroyed by the SNe shock, modifying the grain size distribution and eventually the extinction curve. In H08, the shock destruction is implemented with the destruction efficiency depending on the ambient gas density, which is varied from 0, 0.1, to 1 \( cm^{-3} \). Here 0 \( cm^{-3} \) is the case for no destruction and 1 \( cm^{-3} \) for the most efficient destruction. If the gas density is much larger than 1 \( cm^{-3} \), the dust destruction is so efficient that there would be almost no dust extinction (Nozawa et al. 2007).

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\(^6\) http://www.swift.ac.uk/user_objects/
Figure 1. SEDs of GRB 071025 at the 6605 s post-burst epoch, fitted with models incorporating various extinction curves. The solid lines indicate the best-fit model curves, while the dashed line shows a result with no extinction. The Maiolino model, given as a representative of the SNe-dust extinction curves, fits the data best. The dotted lines for each panel are plotted with no extinction assumption.

For this analysis, we introduce a $Y$-band data point at $t = 6605$ s by interpolating two epochs of data (2653 and 11526 s) from P10. Applying $\alpha = 1.47 \pm 0.06$ of the $I$-band, we estimate $Y = 18.30 \pm 0.21$ mag. We did not add other data sets such as $RIJHK_s$ from P10, since such data do not significantly improve photometric accuracies in the same bands. Figure 2 and Table 2 summarize our findings after the GRB 071025 data are fitted with these models.

First, we discuss whether the mixed or the unmixed core model fits the data better using 25 $M_\odot$ progenitor models as references. The left panel of Figure 2 shows that the unmixed core model fits the data better than the mixed core model. Mixed core produces only oxidized molecules, since most carbons are locked in CO. Extinction is dominated by SiO$_2$ in such cases, regardless of progenitor mass. Since the SiO$_2$-dominated extinction curve monotonically increases with $1/\lambda$ without any change of the slope, it cannot explain the inflexed SED shape of GRB 071025. We find that the same argument applies to models with different progenitor masses; therefore, we will focus on unmixed core progenitors in the following.

Next, we examine if the dust destruction is needed to account for the observed SED. The triple-dot-dashed and the dotted lines represent models with dust destruction at $n_H = 0.1$ cm$^{-3}$ and 1 cm$^{-3}$, respectively. The destruction affects small grains and the effect is reflected in the model SED in the left panel of Figure 2. After the destruction, the extinction curve becomes featureless, resembling the SMC or the Calzetti curves, and the afterglow model SEDs with the dust destruction fit the data as poorly as models with the SMC or the Calzetti curves. Therefore, we conclude that the dust destruction is negligible for GRB 071025. We checked that this conclusion holds for models with other progenitor masses.

Finally, we discuss the most likely progenitor mass of the SNe responsible for the dust. For this, we compare the best-fit

| Extinction Curves$^a$ | $\beta$ | $A_{3000}$ | $\chi^2$/dof |
|-----------------------|--------|------------|--------------|
| None                  | 1.56 $\pm$ 0.11 | ... | 5.10/4-2 |
| Milky Way             | 1.56 $\pm$ 0.11 | $\sim$0 | 5.10/4-3 |
| LMC                   | 1.56 $\pm$ 0.11 | $\sim$0 | 5.10/4-3 |
| SMC                   | 1.05 $\pm$ 0.47 | 0.30 $\pm$ 0.24 | 3.87/4-3 |
| Calzetti              | $\sim$0 | 2.57 $\pm$ 0.07 | 3.94/4-3 |
| Maiolino SNe          | 1.24 $\pm$ 0.17 | 0.77 $\pm$ 0.34 | 0.17/4-3 |
| Hirashita 13 $M_\odot$(U) | 0.86 $\pm$ 0.32 | 1.73 $\pm$ 0.77 | 2.48/5-3 |
| Hirashita 20 & 30 $M_\odot$(U) | 1.54 $\pm$ 0.10 | $\sim$0 | 7.29/5-3 |
| Hirashita 20 $M_\odot$(M) | 1.19 $\pm$ 0.37 | 0.15 $\pm$ 0.15 | 6.44/5-3 |
| Hirashita 25 $M_\odot$(U) | 0.79 $\pm$ 0.30 | 2.65 $\pm$ 1.00 | 0.57/5-3 |
| Hirashita 25 $M_\odot$(M) | 1.26 $\pm$ 0.23 | 0.07 $\pm$ 0.05 | 5.40/5-3 |
| Hirashita 170 $M_\odot$n$_H$ = 0.1(U) | 1.36 $\pm$ 0.20 | 0.77 $\pm$ 0.73 | 6.37/5-3 |
| Hirashita 25 $M_\odot$n$_H$ = 1.0(U) | 1.53 $\pm$ 0.16 | 0.09 $\pm$ 0.88 | 7.26/5-3 |
| Hirashita 170 $M_\odot$(U & M) | 1.54 $\pm$ 0.10 | $\sim$0 | 7.29/5-3 |
| Hirashita 170 $M_\odot$n$_H$ = 0.1(U) | 1.54 $\pm$ 0.10 | $\sim$0 | 7.29/5-3 |

Note. $^a$ U: unmixed core and M: mixed core.
models with the 13, 20, 25, 30, and 170 $M_{\odot}$ progenitors with unmixed core and no dust destruction (the right panel of Figure 2). Figure 2 shows that the models with a progenitor mass of 13 or 25 $M_{\odot}$ fit the data significantly better than the others (the $\chi^2_{\text{red}} \lesssim 1$ versus ~4). This is because the inflexed SED shape between the $I$- and $K_s$-bands can be explained by extra absorptions at the rest frame 1200–2000 Å and around 3000 Å due to the increased contribution of carbon grains (13 $M_{\odot}$), or Mg$_2$SiO$_4$ and FeS grains (25 $M_{\odot}$) with respect to Si grains. The 30 $M_{\odot}$ progenitor model fails to fit the data because of the excessive increase of Si grains. The 170 $M_{\odot}$ model, given as a representative case for pair-instability supernovae, which could be abundant in the early universe (Heger & Woosley 2002), also gives poor fits to our data. This results from the high contribution of Si grains which make the curve look more or less monotonically increasing and the deficiency of the extra extinction from Fe that introduces a plateau in the model SED at shorter wavelengths.

5. SUMMARY

We examined the dust property of a red afterglow of GRB 071025. Analysis of our own data set that is largely independent from P10 supports the evidence for the existence of SNe-dust at $z \sim 5$. Furthermore, using the SNe-dust extinction curves of H05 and H08, we find that models with 13 and 25 $M_{\odot}$ progenitors with unmixed core and no dust destruction give the best fit to the data. Given uncertainties in the model, we suggest that the most plausible progenitors of the SNe-dust are intermediate mass stars with 10–30 $M_{\odot}$.

We thank R. Chary and D. Perley for useful discussions. This work was supported by the Korea Science and Engineering Foundation (KOSEF) grant No. 2010-0000712, funded by the Korea government (MEST). We acknowledge the use of data obtained with the LOAO 1-m telescope operated by KASI and the Canada–France–Hawaii Telescope, and data supplied by the UK Swift Science Data Centre at the University of Leicester. This work is partly supported by NSC-99-2112-M-008-003-MY3 (Y.U.) and NSC-99-2112-M-001-002-MY3 (K.Y.H.). Access to the CFHT was made possible by the ASIAA, Taiwan.

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