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DUST PROPERTIES AT $z = 6.3$ IN THE HOST GALAXY OF GRB 050904

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ABSTRACT

We investigate the dust extinction properties in the host galaxy of GRB 050904 at $z = 6.29$ by analyzing simultaneous broadband observations of the optical and UV afterglow at three different epochs. We show that the peculiar afterglow spectral energy distribution (SED) observed at 0.5 days and at 1 day after the burst (1.6 and 3 hr rest frame) cannot be explained by dust reddening with any of the extinction curves observed at low redshift. Yet, the extinction curve recently inferred for the most distant BAL QSO at $z = 6.2$ nicely reproduces the SED of GRB 050904 at both epochs. Our result provides an additional, independent indication that the properties of dust evolve beyond $z \sim 6$. We discuss the implications of this finding within the context of the dust production mechanisms through the cosmic ages.

Subject headings: dust, extinction — galaxies: high-redshift — galaxies: ISM — gamma rays: bursts

1. INTRODUCTION

Until recently, the investigation of the ISM at high redshift has been mostly based on systems observed in absorption along the line of sight of bright quasars or in Lyman break galaxies. However, the bright emission of gamma-ray bursts (GRBs) and the broad redshift distribution of these objects (from local to $z = 6.3$, so far) has highlighted GRBs as a new, independent tool to investigate the ISM at high redshift.

GRB 050904 was a bright, long burst occurred at redshift $z = 6.29$, the most distant GRB identified so far. Previous studies have shown that the progenitor was a massive star embedded in a dense, metal-enriched molecular cloud (Campana et al. 2007; Frail et al. 2006). This burst presents two peculiarities with respect to lower redshift GRBs. First, X-ray data at early times (within the first few minutes) shows a large column of gas along the line of sight, but little associated optical dust extinction (Campana et al. 2007). Note also that the gas absorption is found to decrease rapidly within the first few hours. Second, its afterglow presents a peculiar flux suppression at $\lambda_{\rm rest} \sim 1300$ Å (in addition to the Lyα blanketing effect), at 0.5 days after the burst, while the flux redward 1600 Å shows negligible extinction (Haislip et al. 2006).

In this work we further investigate these issues, and in particular the latter, in terms of dust properties. We collect broadband afterglow observations (from near-IR to X-rays) at three epochs after the burst, and fit the data with an intrinsic power-law and dust reddening. In addition to the "standard" extinction curves typically assumed to model dust absorption in extragalactic objects, and in lower redshift GRBs (Stratta et al. 2004, 2005; Kann et al. 2006), we also tested the extinction curve inferred from the most distant broad absorption line (BAL) QSO, at $z = 6.2$ (Maiolino et al. 2004). We show that the latter extinction curve is in excellent agreement with the data of GRB 050904, providing further, independent evidence for an evolution of the dust properties at $z > 6$. We also discuss the implications of our results for the origin of dust at high redshift.

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2. MULTIBAND SPECTRAL ANALYSIS

2.1. *X-Rays and Intrinsic SED*

The X-ray spectra have been extracted in the 0.3–10.0 keV energy range from *Swift* X-ray Telescope (XRT) data following standard procedures. At ∼0.5 days after the burst trigger t_0 (2005 September 5.07785 UT), the X-ray emission shows a strong flaring activity (Cusumano et al. 2007; Gendre et al. 2006). In order to avoid any possible spectral contamination from the flares in our continuum analysis, we did not take into account data in temporal intervals where flares were present. We fit the 0.3–10.0 keV data by assuming an absorbed power law. We find evidence for little absorption in excess of the Galactic value ($N_{\rm H}^{\rm Gal} = 5 \times 10^{20}$ cm^{-2}; Dickey & Lockman 1990), in agreement with the analysis at late times by Campana et al. (2007). The best-fit spectral energy index is $\alpha = 1.2 \pm 0.2$ ($F_\nu \propto \nu^{-\alpha}$).

This is significantly steeper than the spectral index measured just after the GRB event, suggesting that the synchrotron spectral break shifted toward lower energies between the first XRT observation, ∼3 minutes after the GRB event, and the observations at 12 hr (in agreement with Cusumano et al. 2007).

The X-ray emission after 0.5 days decreases rather sharply, preventing a detailed spectral analysis after this epoch. Thus, we are able to directly compare the optical fluxes with the X-ray spectrum only at 0.5 days after the burst trigger. However, the spectral and temporal properties of this afterglow indicate that the cooling frequency is redward of the optical range already few hours after the burst (Kann et al. 2007; Frail et al. 2006; Cusumano et al. 2007). As a consequence, no spectral break is expected between the X-rays and the optical energy range at any of the epochs of our analysis, nor the power-law index is expected to change in such a time interval. Therefore, we can safely assume that the intrinsic GRB spectrum at 0.5 days (observer frame) is a single power law extending from the X-ray to the optical. At 1 and 3 days we assume that the intrinsic SED has the same power-law index as at 0.5 days.

2.2. *Optical-NIR*

In order to build a broadband SED and investigate its possible temporal variations, we collected multiband optical and near-IR photometry at three epochs, 0.5, 1, and 3 days after the burst trigger t_0 (observer frame). These specific epochs were chosen because both near-IR and z-band photometry (which

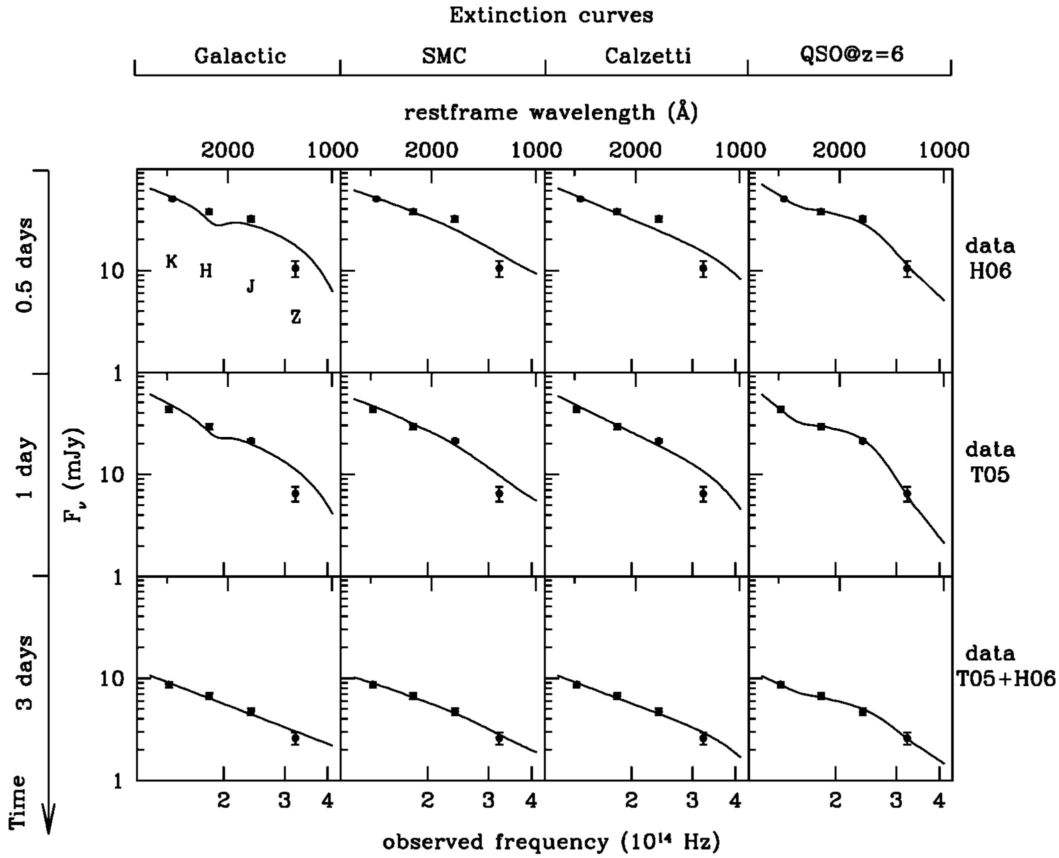

FIG. 1.—Optical-UV rest-frame SED of GRB 050904 at 0.5 (*top*), 1 (*middle*), and 3 (*bottom*) days after the burst (observer frame). The corresponding observed bands are marked on the top left panel. The source of data at each epoch are reported on the right-hand side (H06: Haislip et al. 2006; T05: Tagliaferri et al. 2005). At each epoch we show the best fit with each the four extinction curves shown in Fig. 2, as indicated at top of each column.

are crucial to investigate the rest-frame UV SED) were obtained around these times. More specifically, at ~0.5 days after the burst we used *z*, *J*, *H* photometry obtained with the UK Infrared Telescope (UKIRT) and K' photometry obtained with the Infrared Telescope Facility (IRTF; Haislip et al. 2006). At ~1 day after the burst we used *J*,- *H*-, K_s-, and *z*-band photometry obtained with ESO/VLT by Tagliaferri et al. (2005). At ~3 days after the burst we used *J*, *H*, K_s photometry from Tagliaferri et al. (2005) and z' obtained with Gemini South by Haislip et al. (2006).

Small temporal differences between the times of each individual observation for the three selected epochs were accounted for by assuming that the optical-UV afterglow declines with time as a broken power law. More specifically, the best-fit indices to the light curve obtained by Tagliaferri et al. (2005) are $\delta_1 = -0.72 \pm 0.17$, $\delta_2 = -2.4 \pm 0.4$, and a break at $t_b = 2.6 \pm 1$ days after the burst (see also Kann et al. 2007).

We corrected the observed magnitudes for the Galactic extinction toward the direction of this burst $[E(B-V) = 0.066]$ by assuming the Cardelli et al. (1989) extinction curve with $R_V = A_V/E(B-V) = 3.1$.

Fluxes in the *z* band were corrected for IGM Lyα blanketing effect by renormalizing the afterglow spectrum obtained by Kawai et al. (2006) (at 3 days) so that its convolution with the specific *z* filter profile (including the detector response) yields the photometry observed at each epoch. From the renormalized spectrum we derived the continuum flux density at 9300 Å (i.e., just redward of the damped wing of the IGM Lyα absorption), corresponding to $\lambda_{\rm rest} = 1275$ Å. As we shall see in § 3.1, there is only little and marginal evidence for any variation of the (rest-frame) UV SED between the epoch of the Kawai et al. (2006) spectrum (3 days) and the previous epochs. This justifies the extension of the IGM Lyα blanketing correction obtained at 3 days to the other epochs. Note that the *z*-band photometry in the three epochs is obtained with quite different filters at different telescopes. In particular, the *z* filter (FORS2 at VLT) used by Tagliaferri et al. (2005) at 1 day after the burst is much redder than the *z*-band filters used by Haislip et al. (2006) at the other two epochs. As a consequence, the *z*-band correction factors for Lyα blanketing effect are significantly different at the three epochs; specifically, a factor of 3.02 at 0.5 days, 1.27 at 1 day (i.e., nearly unaffected by IGM absorption), and 2.20 at 3 days.

3. DUST PROPERTIES

3.1. *Evidence for Dust Evolution at $z > 6$*

At 0.5 days after the burst, a peculiar flux suppression in the *z* band ($\lambda_{\rm rest} \approx 1275$ Å) has been detected by Haislip et al. (2006) after accounting for IGM Lyα absorption. We also find the same *z*-band flux suppression at 1 day after the burst, with a totally independent set of data (Fig. 1). The flux drop is so sharp that Haislip et al. (2006) ruled out dust reddening as a possible cause.

We further investigate the dust extinction scenario to tackle the issue of the peculiar *z*-band flux suppression. In addition

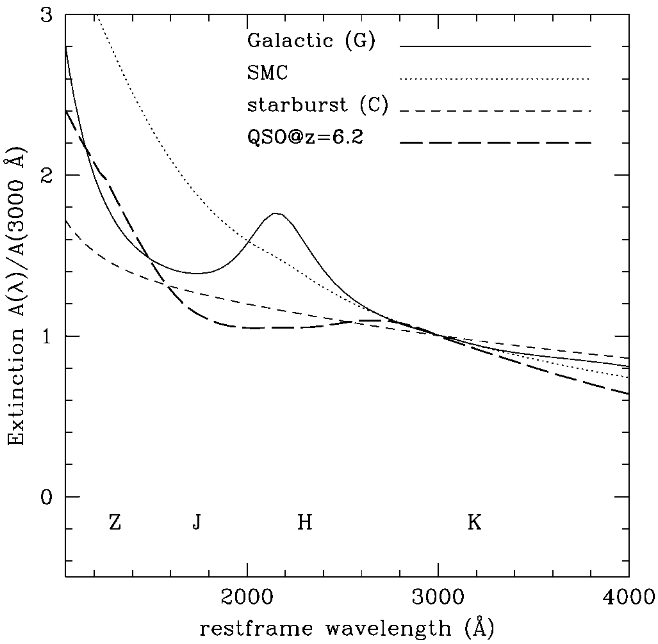

FIG. 2.—Extinction curves tested in our analysis, normalized to $\lambda_{rest} = 3000$ Å. The photometric bands are shown shifted to the corresponding central wavelengths at the rest frame of GRB 050904 at $z = 6.29$. The extinction curve inferred for the QSO at $z = 6.2$ (Maiolino et al. 2004) is directly observed at 1260 Å < λ_{rest} < 3300 Å, while it is extrapolated beyond these limits by using the theoretical SN dust extinction curve. However the latter extrapolation is unimportant, since for GRB 050904 at $z = 6.29$ we essentially use the same observed bands as for the QSO at $z = 6.2$.

to the standard extinction curves inferred in the local universe (Galactic, SMC, and starburst attenuation curve, from Cardelli et al. 1989; Pei 1992; Calzetti et al. 1994)[3], we also consider the extinction curves computed by Maiolino et al. (2001) based on a dust model skewed toward large grains, which apply to some low-z GRBs (Stratta et al. 2004, 2005), and the extinction curve inferred by Maiolino et al. (2004) for the most distant BAL QSO at $z = 6.19$ (hereafter the "QSO at $z = 6$" extinction curve), illustrated in Figure 2.

From the optical-to-X-ray spectral analysis, we find that at $t_0 + 0.5$ days the optical data require additional extinction in addition to the Galactic value to reproduce the flux values expected from a power law with the same spectral index as the X-ray spectrum (see § 2). No "standard" extinction curve can reproduce the observed SED with the peculiar flux suppression in the z band, as shown in the first three panels at the top of Figure 1. The extinction curves from a dust model skewed toward larger grains also fail to reproduce the flux in the z band, although they provide a better fit to the J, H, and K photometry than the standard extinction curves. The only extinction curve that provides an acceptable fit is the QSO at $z = 6$ one with $A(3000$ Å$) \sim 1$ mag (Fig. 1, *top right panel*). The same result is obtained by using the independent set of data at $t_0 + 1$ day (Fig. 1, *second row of panels*).

The statistics of the fits with the different extinction curves (along with the inferred absolute extinctions) are given in Table 1. It is clear that the improvement of the fit with the QSO at $z = 6$ extinction curve is highly significant at both 0.5 and 1 days after the burst.

[3] In the case of the starburst attenuation curve, we use the Calzetti et al. (1994) expression for the UV continuum that, at 3000 Å, is 0.4 times the extinction for the ionized gas.

TABLE 1
BEST-FIT PARAMETERS OF THE GRB 050904 SED AT DIFFERENT EPOCHS

Extinction Curve	A(3000 Å)[a] (mag)	χ^2/dof[b]
	$t - t_0 = 0.5$ day	
Galactic	0.53 ± 0.08	38.7/(12–2)
SMC	0.33 ± 0.06	33.3/(12–2)
Calzetti	0.43 ± 0.06	31.4/(12–2)
QSO at $z = 6$	0.89 ± 0.16	15.1/(12–2)
	$t - t_0 = 1.0$ day	
Galactic	0.43 ± 0.18	27.9/(4–2)
SMC	0.48 ± 0.08	17.4/(4–2)
Calzetti	0.70 ± 0.06	24.3/(4–2)
QSO at $z = 6$	1.33 ± 0.29	0.01/(4–2)
	$t - t_0 = 3.0$ day	
Galactic	<0.3 (2 σ)	3.2/(4–2)
SMC	0.27 ± 0.07	1.1/(4–2)
Calzetti	0.40 ± 0.07	2.2/(4–2)
QSO at $z = 6$	0.46 ± 0.28	0.6/(4–2)

[a] Extinction at 3000 Å. Errors are at 1 σ confidence level.
[b] Note that at 0.5 days after the burst, X-ray data were included in the fit (see § 2.1), thus yielding a larger value for the degrees of freedom (dof).

This result is still true at 3 days, although with a lower significance. We also note that at the latter epoch there is marginal evidence for a decrease in extinction (Table 1). This could be regarded as an indication of dust destruction by the blast wave 3 days after the burst, or alternatively that at this late epoch the fireball has a projected size larger than the obscuring cloud, and therefore the emitting region is less absorbed. However, since the decrease of extinction at 3 days is only marginally significant, we do not discuss this issue further, and focus only on the extinction curve properties.

Our result indicates that two totally different classes of objects at $z \geq 6$, QSOs and GRBs, are characterized by the same extinction curve, which is different from that observed at lower redshift. More specifically, the QSO at $z = 6.2$ investigated by Maiolino et al. (2004) and the GRB at $z = 6.3$ investigated in this paper provide independent evidences for an evolution of the dust properties beyond $z \sim 6$.

3.2. *The Nature of Dust at $z > 6$*

A transition in the properties of the dust at $z \sim 5$–6 is theoretically expected. Indeed, the major source of dust in the local universe are the envelopes of AGB stars, which require about 1 Gyr to evolve in large numbers (Dwek 2005; Morgan & Edmunds 2003; Marchenko 2006; Todini & Ferrara 2001). At $z > 5$ the age of the universe is less than 1 Gyr, and therefore AGB stars fall short of time to produce enough dust. As a consequence, galaxies at $z > 5$ should be devoid of most of the dust, since the major source of dust (AGBs) is missing. Nonetheless, significant masses of dust are still observed in distant QSOs up to $z = 6.4$ (e.g., Bertoldi et al. 2003; Priddey et al. 2003; Robson et al. 2004; Beelen et al. 2006). Theoretical models have shown that an alternative source of dust on short timescales is core-collapse supernovae, which could therefore be the primary dust production mechanism in the early universe (Todini & Ferrara 2001; Nozawa et al. 2003; Dwek 2005; Morgan & Edmunds 2003; Marchenko 2006). From an observational point of view, the actual efficiency of dust production in SN ejecta is still not clear (Sugerman et al. 2006; Ercolano et al. 2007; Krause et al. 2004; Wilson & Batrla 2005; Green et al. 2004). However, both Maiolino et al. (2004) and Hirashita et al. (2005) found a good agreement between the extinction curve expected from SN dust and the extinction curve observed in the most distant BAL QSO at $z = 6.2$ (QSO at $z = 6$), suggesting that in the latter object dust is predominantly produced by SNe. The result obtained in this paper indicates that in the host of GRB 050904 as well, dust is likely produced mostly by SNe. Altogether, these findings suggest that, more generally, regardless of the specific class of object, at $z > 6$ SNe are the main sources of dust.

Independent evidence for different properties of the dust in the host of GRB 050904 comes from a comparison between the large column of absorbing gas observed at early times ($N_H \sim 8 \times 10^{22}$ cm^{-2}; Cusumano et al. 2007; Campana et al. 2007) and the little associated extinction observed in the optical-UV rest frame. More specifically, the latter implies an A_V/N_H ratio more than 50 times lower than the Galactic value, which is unprecedented in lower redshift GRBs (Stratta et al. 2004, 2005). Campana et al. (2007) ascribe this effect to dust mostly composed of silicate grains (possibly produced by pair-instability SNe) which are destroyed soon after the burst. Here we note that, independent of the dust composition, a strongly reduced dust-to-gas ratio is naturally expected at $z \sim 6$ as a consequence of the dust evolutionary timescales. Indeed, as discussed above, the lack of an important contribution to dust production from AGB stars at $z > 6$ makes the dust-to-gas ratio in the early universe necessarily much lower than observed locally.

Furthermore, we note that the variation of dust content as a function of redshift may be at the origin of the shortage of optical GRB detections at lower redshift. Indeed, only ~50% of the *Swift* GRBs have shown an optical counterpart, even by taking advantage of the quick *Swift* GRB localization (Fiore et al. 2007). The larger dust content at $z < 6$, expected by the dust evolutionary scenarios, may prevent the optical detection of low-z GRBs. This issue will be discussed more extensively in a forthcoming paper.

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