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X-RAY HEATING OF DUST IN GAMMA-RAY BURST ENVIRONMENTS

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ABSTRACT

We report observations in the R-band of the afterglow of GRB 090618 with the SARA 0.9m telescope at Kitt Peak National Observatory. The lightcurve can be fit with a broken power law, with a possible jet break at $t_j \sim 0.74$ days. The foreground extinction to this burst is $A_R = 0.036$ while the extinction in the host galaxy is undetermined. We also carry out a study of dust destruction by X-ray heating due to the early emission from gamma-ray bursts. We find that dust can be destroyed to distances of a few parsecs, so that the local environment of a GRB may not contribute significantly to the possible obscuration. These results are consistent with earlier results based on dust sublimation from optical/UV flashes. While multiband photometry of GRB afterglows offers a powerful probe of dust evolution to large redshifts, the effects of the intense X-ray emission on dust in the vicinity of the burst must be taken into account.

Subject headings: gamma rays: bursts—dust, extinction—X-rays

1. INTRODUCTION

Interstellar dust particles are ubiquitous in the universe, and play important roles in various astrophysical environments. Molecular chemistry in the interstellar medium (ISM) involves interactions on the surface of dust particles: starlight is reprocessed into the infrared part of the electromagnetic spectrum and dust-gas coupling is important in the formation of stars and protoplanetary systems (for a recent review of "dust astronomy" see Grün et al. 2005). The observed extinction curve of the Milky Way shows a strong wavelength dependence and a 'bump' at 2175 Å, which is commonly interpreted as resulting from graphite and polycyclic aromatic hydrocarbons (Draine 2009). Additional features are found at 9.7 μm and 18 μm corresponding to modes of Si-O. For the purpose of this study it is assumed that dust particles are spherical, amorphous, and composed of graphite or silicate, as is commonly assumed in models of dust extinction (Pei 1992; Fruchter et al. 2001; Mathis et al. 1977; Kim et al. 1993). Furthermore, we assume, since the GRB that we analyzed is at redshift z=0.54, that dust properties in the vicinity of gamma-ray bursts (GRBs) are similar to those observed in the nearby universe.

Dust can significantly affect the afterglow of the gamma-ray burst through extinction and reddening (e.g., Klose et al. 1998; Kann et al. 2006). The extinction occurs mostly in the blue part of the optical spectrum, while the longer wavelength regime is less affected. Optical afterglows of GRBs fade rapidly (with flux approximately scaling inversely with time), thus requiring a rapid response by ground-based observatories. Despite an enormous effort for such rapid responses with robotic telescopes, a significant fraction of all GRBs appear to have no detectable optical afterglow emission (e.g., Akerlof & Swan 2007). Limitations in response capabilities, adverse weather conditions, high redshifts, and extinction are possible causes for these so-called 'dark bursts' (Djorgovski et al. 2001). Recent studies suggest that obscuration by dust is most likely the dominant factor for explaining the dark burst phenomenon (Perley et al. 2009; Zheng et al. 2009). Similar to the foreground extinction from the Milky Way, the dust in the host galaxies of GRBs is not likely to contribute to the often observed values in excess of $A_v \sim 1$ magnitude. The association of long duration GRBs with massive stars (e.g., Woosley & Bloom 2006) suggests that the dense environments of star forming regions is responsible for the observed extinction, as originally suggested by Paczynski (1998). However, the intense radiation from the GRB and its afterglow is capable of destroying dust out to significant distances of order 10 pc (e.g., Waxman & Draine 2000; Fruchter et al. 2001). Here we describe a highly simplified model of dust heating and cooling in the vicinity of a GRB in order to evaluate the possibility of the dense environment causing the observed extinction. We also present afterglow observations with the SARA (Southeastern Association for Research in Astronomy) telescope of GRB 090618.

The paper is organized as follows: in §2 we discuss the observations of GRB 090618 and the extinction it experiences due to the galactic foreground. In §3, we investigate the heating of dust near a GRB due to photoelectric absorption, and determine the equilibrium temperature under the assumption of balance between X-ray heating and radiative cooling. We discuss the distance to which dust may be destroyed and the corresponding reduction in local extinction. Conclusions are presented in §4.

2. AFTERGLOW OBSERVATIONS OF GRB 090618

Using the 0.9m SARA Telescope at Kitt Peak National Observatory (KPNO), CCD images were obtained of the *Swift* detected GRB 090618 (Schady et al. 2009) on the nights of June 18 and 19, 2009 (Updike et al. 2009b,c). The burst occurred at 08:28:29.85 UT and its optical afterglow had an estimated white filter magnitude of 14.4 at 128 s after the trigger (Schady et al. 2009). The location of GRB 090618 as localized by the UVOT instrument on *Swift* is RA=19h 35m 58.69s and DEC=+78° 21m 24.3s with an uncertainty of 0.74 arcseconds (Schady

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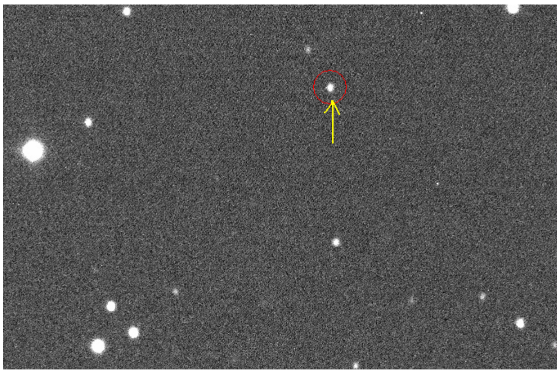

FIG. 1.— One single 45 sec R-band image of GRB 090618, obtained 114 minutes after the trigger with the SARA 0.9m telescope at KPNO. The image is 9 arcmin wide by 6 arcmin tall, and aligned north up and east left.

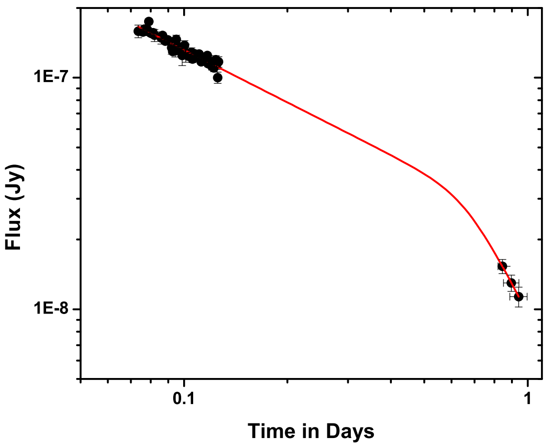

FIG. 2.— The R-band lightcurve of GRB 090618 corrected for foreground extinction of A_R = 0.036 mag (Schlegel et al. 1998). The solid line displays a Beuermann-fit, resulting in an estimated jet break time of t_j = 0.74 days.

et al. 2009). Our observations consisted of a sequence of 45 sec exposures in the R-band, starting 1.5 hours after the trigger and continuing for two hours on June 18; additional observations were obtained on the following day. The images were reduced (stacking where appropriate) using standard IRAF packages for aperture photometry (Figure 1 shows a single 45 sec exposure of the field which clearly reveals the optical afterglow). The field was calibrated relative to USNO B1.0 field stars. The observations with SARA resulted in a detection at $R \sim 17$ an hour and a half after the burst.

Figure 2 shows the flux density (averaged over the R-band as a function of time). The initial decline exhibits the typical decay law ($f_\nu \propto \nu^{-\alpha}$ with $\alpha \sim 1$), but the observations performed on the second night clearly indicate a much more rapid decline. The R-band light curve (see Figure 2) was fit with a broken power-law model (Beuermann 1999) using a Levenberg-Marquardt least-squares algorithm, which resulted in a jet break time of $t_j = 0.74 \pm 0.08$ days, a pre-break slope of α_1= 0.75, and a post-break slope of $\alpha_2 = 3.50$ with a reduced χ^2 of 1.162.

The redshift of GRB 090618 is $z = 0.54$ (Cenko et al. 2009) and the fluence in the 15-150 keV band is $S \sim 10^{-4}$ ergs cm^{-2} (Sakamoto et al. 2009). The isotropic equivalent energy of the burst is given by

$$E_{ISO} = 4\pi\ S\ D_L^2\ (1+z)^{-1} \text{ ergs} \tag{1}$$

where the redshift implies a luminosity distance of $D_L = 9.5 \times 10^{27}$ cm for the parameters of standard Λ_{CDM} cosmology (Komatsu et al. 2009). The $(1+z)^{-1}$ factor corrects for time dilation. These values imply an isotropic equivalent energy of $\sim 10^{53}$ ergs. The actual energy involved in the burst is significantly less than the above estimate due to the geometric beaming. The jet opening angle can be determined from the observed jet break time (Frail et al. 2001)

$$\theta_j = 0.057 \left(\frac{t_j}{1\,\text{day}}\right)^{3/8} \left(\frac{1+z}{2}\right)^{-3/8} \left(\frac{E_{ISO}}{10^{53}\,\text{ergs}}\right)^{-1/8} \times \left(\frac{\eta_\gamma}{0.2}\right)^{1/8} \left(\frac{n}{0.1\,\text{cm}^{-3}}\right)^{1/8}, \tag{2}$$

where the jet break time is given as t_j, $\eta_\gamma = 0.2$ (Guetta et al. 2001) is the efficiency with which the shocks convert energy into gamma rays, and n is the density of interstellar hydrogen. The 'jet break time' refers to the time (usually measured in days) after the onset of the burst at which the bulk Lorentz factor of the ejecta has decreased to the point where the relativistic beaming angle and the opening angle of the geometric GRB jet are comparable. After that point in time the observer notices as faster decline of the lightcurve, due to the fact that the full emissing surface area of the jet is now contributing, while before the jet-break it was only a small part of the emitting surface of the jet from which photons can reach the observer. The interplay between the hydrodynamics of a relativistic jet, and the geometry of the outflow, results in a time-feature (the jet-break time) that allows us to in fact measure the opening angle of the jet, and thus determine the true GRB energy.

This gives a jet opening angle of 0.073 radians. The energy emitted by the jet is then given as follows (Frail et al. 2001)

$$E_\gamma \simeq \frac{\theta_j^2}{2} E_{ISO}, \tag{3}$$

which yields a corrected energy estimate of $E_\gamma \sim 3 \times 10^{50}$ ergs. This is consistent with typical values derived in Frail et al. (2001) but somewhat smaller than values found in the more recent study by Bloom et al. (2003).

2.1. *Extinction*

There are two main sources of extinction: dust present in the host galaxy and dust in the foreground, i.e. the local Milky Way environment. The extinction at a given frequency follows from the line of sight integral over the particle density, convolved with an integral over the particle size distribution (e.g., Kim et al. 1993)

$$\tau_\nu = A_\nu/1.086 = \int dl \int_0^\infty \pi a^2 Q_{e,\nu}(a) n(a) da \tag{4}$$

where a represents the radius, $n(a)$ is the differential number density of dust particles per unit volume per unit radius, and $Q_{e,\nu}$ is the extinction efficiency. From the optical properties of dust particles one can determine the extinction for given assumptions about the composition, shape, and size distribution of the dust. In addition, the spatial distribution of the dust density needs to be known to evaluate the above integral for a particular line of sight. In practice an estimate of the foreground extinction in our galaxy is based on the detailed dust maps provided by Schlegel et al. (1998). At the position of GRB 090618, these maps yield $E(B-V)$=0.013 mag, which corresponds to a total extinction in the R-band of $A_R = 0.036$ mag.

Due to the fact that we only carried out single band photometry for this afterglow, we are unable to derive any extinction that may have taken place in the vicinity of the GRB or along the line of sight through the ISM of the host galaxy. Extinction of GRB afterglows due to dust in evolving host galaxies was considered in Updike et al. (2009a), who finds that, in general, galaxies provide only small opacities when one considers random orientations of the host galaxies and generic double exponential density profiles. However, it is conceivable that significant extinction could come from the local environment around the GRB. After all, GRBs are known to be associated with massive stars and thus may still be surrounded by extensive gaseous structures in which their formation took place. However, even if local dust is abundant, it may not survive due to the intense optical-UV-X-ray emission from the burst. In the next section we consider the question of dust destruction with a simple model involving photoelectric heating and radiative cooling as the primary means of photon interaction with the dust.

3. DUST IN THE VICINITY OF A GRB

To address the question of dust survival we first consider the basic dependence on burst parameters, such as total energy and spectral energy distribution. The isotropic equivalent energy of a GRB is given by Equation 1, and is on the order of 10^{53} ergs. Emission from a GRB is beamed, and we are only concerned with the dust located within the beam. Heating of the particles by photoelectric absorption then depends on the photon flux the particle receives at a given distance, D, from the GRB. To estimate this flux, $f(D)$, the photon luminosity of the GRB needs to be determined. We do so with the help of a simple ansatz for the spectrum, and a scaling with energy relative to a standard value of $E = 10^{53} E_{53}$ ergs. We assume that the temperature of a dust particle can reach an equilibrium during the duration of the burst and that it will be destroyed (by sublimation) when this equilibrium exceeds a particular value. Heating is thus assumed to be balanced by radiative cooling which depends on the particle size and its optical properties. Since we assume that dust in GRB host galaxies is basically the same as the dust we find in the Milky Way, we employ a range of dust particle sizes from 0.005 to 1 μm (Mathis et al. 1977).

3.1. *Photoelectric Heating Rate*

Dust can be destroyed by high energy photons and collisions with particles as well as grain-grain interactions (for a recent review see Jones 2004). Here we consider only the effects of heating through photoelectric absorption in the keV X-ray regime (see also Fruchter et al. 2001). The thermal energy of a dust particle increases according to:

$$\dot{E}_H = \int f_\epsilon(D) \epsilon \sigma_g (1 - e^{-\tau}) d\epsilon \;\; \text{ergs s}^{-1} \tag{5}$$

where σ_g is the geometrical cross-section of the dust particle, $f_\epsilon(D)$ is the specific photon flux from the GRB at the position of the dust particle, and ϵ is the energy of a photon. The factor in brackets corresponds to the fraction of the photons that are absorbed by the dust particle. Using a Taylor expansion about τ=0 and assuming that τ is small, the factor $1 - e^{-\tau}$ reduces to τ, and is given by

$$\tau = \tau(\epsilon) = n_{atoms} \sigma(\epsilon) \; L \tag{6}$$

where $\sigma(\epsilon) = \sigma_\circ \epsilon^{-3}$ with $\sigma_\circ$=10^{-22} cm^2. The photon energy in this expression is assumed to be measured in units of keV. We assume that the dust particles are porous with a density of 1 g cm^{-3}. The number density of atoms (n_{atoms}) within the dust particle is then given by the assumed composition, either graphite or silicate. L is the average geometric propagation depth of a spherical dust particle given by

$$L = \frac{1}{\pi a^2} \int_0^a 2\pi r \; l(r) dr = \frac{4}{3} a \tag{7}$$

The differential photon flux is given by

$$f_\epsilon(D) = \frac{\dot{N}_\epsilon(\epsilon)}{4\pi D^2} \tag{8}$$

where

$$\dot{N}_\epsilon(\epsilon) = A \epsilon^\alpha \exp(-\epsilon/\epsilon_\circ). \tag{9}$$

Using $\alpha \sim -1$ and $A = 6 \times 10^{59} E_{53}$ over the energy range from 0.1 to 10^4 keV, we obtain the following heating rate

$$\dot{E}_H \sim 1 \times 10^5 a_{\mu m}^3 D_{pc}^{-2} \eta_g^{-1} \;\; \text{ergs s}^{-1} \tag{10}$$

where η is the mass per mole of either a silicon or carbon atom. We normalize particle radii to one micrometer and measure the distance from the GRB in parsecs.

3.2. *Radiative Cooling Rate*

Now we consider radiative cooling of the dust particles, making the assumption of spherical geometry. If the radiating dust particles were to follow a simple blackbody law, one would expect the energy loss rate to have the familiar form $\dot{E}_C = 4\pi a^2 \sigma T^4$. However, the radiative absorption/emission efficiency $Q(\lambda, a)$ varies signficantly with wavelength. Thus the correct radiative loss rate is given by (e.g., Tielens 2005)

$$\dot{E}_C = 4\pi a^2 \int Q(\lambda, a) \pi B_\lambda(T) d\lambda \quad \text{ergs s}^{-1} \; . \tag{11}$$

This equation can be transformed into

$$\dot{E}_C = 4\pi a^2 \sigma_{SB} T^4 Q_P(T) \; \text{ergs s}^{-1} \tag{12}$$

where σ_{SB} is the Stefan-Boltzmann constant and $Q_P(T)$ is the Planck averaged efficiency (Tielens 2005). Using the common approximation $Q(\lambda, a) = Q_0(\lambda_0/\lambda)^\beta$ for $\lambda >$

$\lambda_0 = 2\pi a$ and $\beta \sim 1-2$, the Planck averaged efficiency is given by

$$Q_P(T) = \frac{(2\pi a)^\beta}{\sigma_{SB} T^4} Q_0 \int_0^\infty \lambda^{-\beta} \pi B_\lambda(T) d\lambda \ . \tag{13}$$

After integrating, $Q_P(T)$ can be expressed as

$$Q_P(T) = 15\pi^{-4}(\beta+3)!\zeta(\beta+4)Q_0 \left(akT/\hbar c\right)^\beta,$$

where $\zeta(x)$ is the Riemann-Zeta function. For $Q_0 = 1$, we find a cooling rate of

$$\dot{E}_C = 12 \ a^3 T_3^5 \quad \text{ergs s}^{-1}. \tag{14}$$

The above procedure can be compared to that given by Fruchter et al. (2001) with the exception of $Q(\lambda, a)$ being represented by Q_a. In this instance Q_a is the absorption efficiency of the grain given by $8\pi a/\lambda \times \mathrm{Im}[(m^2 - 1)/(m^2 + 2)]$ (Fruchter et al. 2001), where the Im indicates the imaginary part. Following Fruchter et al. (2001), m represents the sum of the real and complex indices of refraction of the grain material ($m = n + ik$) and $\mathrm{Im}[(\mathrm{m}^2-1)/(\mathrm{m}^2+2)] \sim 0.065$. Selecting a wavelength for which the Planck function becomes a maximum, Fruchter et al. (2001) derives the following equation:

$$\dot{E}_C = 3 \times 10^{-3} \ a_{-1}^3 \ T_3^5 \ \Phi \ \text{ergs s}^{-1} \tag{15}$$

where particle size, a, is now normalized to 10^{-1} μm and Φ is a composition dependent factor. For graphite, $\Phi \approx 3$ and for silicates $\Phi \approx 0.3$. Converting a to microns, this implies

$$\dot{E}_C = (1-10) a^3 T_3^5 \ \text{ergs s}^{-1}, \tag{16}$$

which is consistent with the results derived above (Eq. 14).

3.3. *Equilibrium Temperature and Dust Destruction*

Equating the heating rate and the cooling rate, the dust particle acquires an equilibrium temperature given by

$$1 \times 10^5 D_{pc}^{-2} \eta_g^{-1} = (1-10) T_3^5, \tag{17}$$

which is independent of particle size. We do not consider the time dependence of the temperature but assume that equilibrium is established on a time scale that is shorter than the duration of the GRB. If the grain temperature exceeds $T \approx 2300$ K, we further assume that the particle is destroyed via sublimation (Waxman & Draine 2000). This critical temperature thus corresponds to a dust destruction distance of 4-8 pc, for graphite and silicate, respectively. If the gamma-ray burst is located inside a giant molecular cloud (GMC) of typical size, $R \approx 10$ pc, one would expect several magnitudes of visual extinction (e.g., Carroll & Ostlie 2007). However, the dust destruction derived above suggests that a significant fraction of the dust along the line of sight through the GMC is destroyed, which would imply less obscuration.

4. CONCLUSIONS

The origin of the large fraction of optically dark GRBs remains an open question, although recent studies suggest that extinction is the most likely culprit (Perley et al. 2009; Zheng et al. 2009). As extinction along random lines of sight through the disks of spiral galaxies does not typically yield extinction values larger than $A_\lambda \sim 1$, the site for significant extinction is perhaps related to the environments in close proximity to the GRB. The association of long duration GRBs with supernovae (Woosley & Bloom 2006) naturally leads to the consideration of molecular clouds, which are large enough and dense enough to exhibit the required substantial dust columns. However, dust in the vicinity of a GRB may not survive the ionizing radiation from the GRB and thus dust destruction may quickly render even a molecular cloud transparent (Waxman & Draine 2000). The destruction of dust particles by the optical and UV emission from GRBs was considered in detail by Waxman & Draine (2000) and Fruchter et al. (2001), and these authors showed that dust can indeed be destroyed to distances of order 1 to 10 pc.

Whether or not a GRB is almost always followed by a luminous optical/UV flash is not clear yet. However, observations during the *Swift* era have established that nearly all GRBs are followed by an X-ray afterglow (O'Brien & Willingale 2008). Therefore, we consider the heating of dust by photoelectric absorption in order to assess the question of dust survival. Considering the balance of X-ray heating and radiative cooling we determine the equilibrium temperature attained by a dust particle as a function of distance from the GRB. The simplified model of heating and cooling employed in our study implies that the equilibrium temperature is independent of particle size. A small dependence on particle composition however does exist. We find that sub-micrometer graphite particles exceed the critical sublimation temperature found by Waxman & Draine (2000) for distances as large as 4 pc. For silicates this range of destruction increases to 8 pc. These ranges of course depend on the assumptions made about the X-ray spectrum and fluence of the GRB. As these destruction distances are comparable to the sizes of typical molecular clouds, we find that the prompt X-ray emission and the early X-ray afterglow may very well clear the path for subsequent optical emission to emerge unattenuated. If prompt emission from a GRB would always able to evaporate the local dust, the frequently observed large extinction values (Cenko et al. 2008) would be hard to explain. The observed distribution of extinction values would have to be studied by means of Monte-Carlo simulations in which dust evolution and inhomogeneous spatial distributions in GRB host galaxies are considered. Extinction in the afterglows of GRBs offers a valuble tool to probe how dust properties have evolved over cosmic time, but the destructive force of the GRB itself needs to be taken into account in the interpretation of the observations.

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