

DUST ECHOS FROM GAMMA RAY BURSTS

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ABSTRACT

The deviation from the power-law decline of the optical flux observed in GRB 970228 and GRB 980326 has been used recently to argue in favor of the connection between GRBs and supernovae. We consider an alternative explanation for this phenomenon, based on the scattering of a prompt optical burst by $0.1M_{\odot}$ of dust located beyond its sublimation radius $0.1 - 1$ pc from the burst. In both cases, the optical energy observed at the time of the first detection of the afterglow suffices to produce an echo after $\sim 20 - 30$ d, as observed. Prompt optical monitoring of future bursts and multiband photometry of the afterglows will enable quantitative tests of simple models of dust reprocessing and a prediction of the source redshift.

Subject headings: gamma rays: bursts – ISM: dust, extinction

1. INTRODUCTION

The relationship between Gamma Ray Bursts (GRBs) and supernovae has become increasingly interesting over the past year. Though exploding massive stars have long been considered as possible progenitors of GRBs (e.g. Woosley 1993), no evidence existed to support these theories until observations of the afterglow of GRB 980425 suggested an association of the burst with an unusual supernova 1998bw (Galama et al. 1998, Kulkarni et al. 1998). Later reanalysis of the optical afterglow lightcurves of two other bursts, GRB 970228 (Fruchter et al. 1999) and GRB 980326 (Bloom et al. 1999) showed a deviation from the power-law decline expected if the emission is due to synchrotron radiation from electrons accelerated by the blast wave. In both cases a significant excess emission was observed around ~ 30 days after the gamma-ray burst, with simultaneous reddening of the spectrum. Bloom et al. (1999), Galama et al. (1999), and Reichart (1999) attribute this excess to the emission from an underlying supernova event.

The relationship of GRBs to SN explosions is a question of great importance, since it provides a powerful clue to the fundamental nature of these objects. However, the evidence presented so far is circumstantial – the association of GRB 980425 with SN 1998bw is unproven and the excess emission seen from GRB 970228 and GRB 980326 is based upon relatively few actual measurements – and possible alternative explanations need to be seriously considered, if only to strengthen the case for the SN explanation. In this spirit, Waxman & Draine (1999) suggested that the red excess emission observed in GRB 970228 and GRB 980326 is due to dust in the vicinity of the burst progenitor absorbing and then re-radiating the optical/UV flash observed shortly after the recent GRB 990123 (Akerlof et al. 1999) and generally attributed to the reverse shock which propagates into the fireball ejecta (Mészáros, Rees & Papatianassiou 1994, Mészáros & Rees 1997, Panaitescu & Mészáros 1998, Sari & Piran 1999). However, the Waxman & Draine scenario has two shortcomings. Firstly, the equilibrium temperature of dust is limited to ~ 2300 K

and so the emission should peak at $\sim 2(1+z)\mu\text{m}$ (where z is the GRB redshift), although a small amount of higher temperature emission may be produced by the dust as it is sublimating. Secondly, the optical flash is so powerful that the sublimation radius lies beyond ~ 10 pc from the GRB. Thus, in this picture it is rather difficult to reproduce the observed flux in the $0.4 - 0.8\mu\text{m}$ band with a time delay of order a few weeks.

In this letter we propose an alternative explanation, which relies on the *scattering* of the direct optical transient emitted in the first day by dust as the primary source of excess optical radiation. The fundamental point is that in the two observed cases, assuming isotropic emission, the fluence of the *observed transient* exceeds that of the reported excess and the *unobserved transient* is even larger if we extrapolate to earlier times. A fraction of this emission scattered from a radius where dust can outlive the optical transient should therefore produce a delayed echo. As dust absorbs selectively as well as scatters, the echo is likely to be significantly redder than the original optical transient, as reported.

In the next section, we describe our model for the dust scattering properties and then present the results in the context of the observed GRBs in §3. Implications for future tests of our scenario are discussed in §4. We assume $h = 0.6$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$ so that the angular diameter distance of the GRB is $D_A = 1.5 - 2$ Gpc for $0.5 \lesssim z \lesssim 3$.

2. DUST ECHOS

2.1. Sublimation Radius

Waxman & Draine (1999) estimate that dust grains in the path of the optical/UV flash will be effectively sublimated out to a distance

$$R_{\text{sub}} \sim 1 (Q_{\text{abs}} L_{47} / a_{-1})^{1/2} \text{ pc}, \quad (2-1)$$

where $Q_{\text{abs}} \sim 1$ is the absorption efficiency factor for optical/UV photons, $L_{47} \equiv \int d\nu L_{\nu} / 10^{47} \text{ erg s}^{-1}$ is the unbeamed luminosity of the optical transient (OT) in the

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$1 - 7.5\text{eV}$ energy band, $a_{-1} \sim 1$ is the dust grain size in units of $0.1\ \mu\text{m}$. Beyond R_{sub} , only the most refractory grains, like silicates, can survive. Note that the thermal time for a typical dust particle is of order $10^{-4} - 10^{-2}\text{s}$, much shorter than the duration of the optical transient, so that we can treat grains as being in thermal equilibrium with the incident radiation, (which has a pressure $P_{\text{sub}} \sim 0.03\ \text{dyne cm}^{-2}$ at R_{sub}).

The extinction properties of silicate dust particles were computed by Draine & Lee (1984) (see their Fig. 10), for a power-law distribution of particle sizes proposed by Mathis, Rumpl & Nordsieck (1977) to explain interstellar starlight extinction. Based on their results, we take the ratio of the scattering and absorption efficiency factors to be of order $Q_{\text{sc}}/Q_{\text{abs}} \simeq 4$, and the average scattering angle to be $\langle \cos \theta \rangle \equiv \langle \mu \rangle \simeq 0.5$ for observed wavelengths $0.2 - 1(1+z)\ \mu\text{m}$.

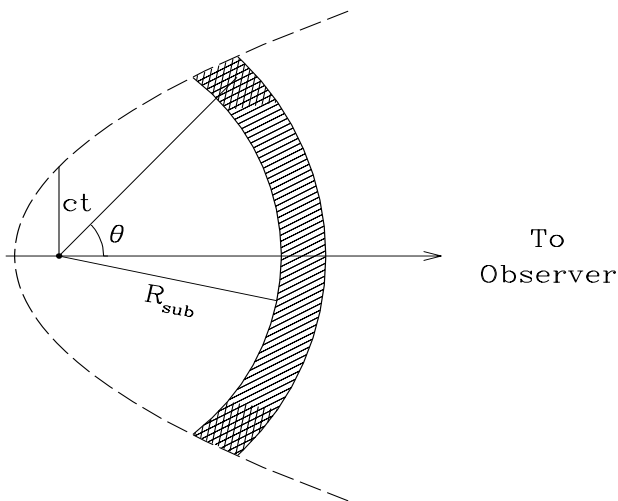


FIG. 1.— A schematic diagram of the GRB environment. The long-dashed line represents the position of the expanding optical/UV photon front at time t in the frame of the GRB. The shaded area shows the region where the dust is not sublimated instantaneously. The heavily shaded area shows the region of the shell from which the scattered radiation is observed while the lightly shaded area represents the regions where the dust is not scattering any more.

2.2. Source Geometry

Fig. 1 shows a schematic picture of the GRB environment observed at time t after the detection of γ -rays. The incident optical transient emission is supposed to be limited to an interval $\Delta t^{\text{OT}} \equiv \Delta t_{\text{ob}}^{\text{OT}}/(1+z) \ll t$ after the GRB, and scattered by dust beyond R_{sub} . We specialize immediately to the case when the dust is associated with an outflowing spherical wind, and the OT is isotropic. (It is straightforward to modify our formalism to accommodate other reasonable assumptions, as discussed in Madau et al. (1999).) As the dust density declines with distance as R^{-2} , the light “echo” observed at time $t_{\text{ob}} = t(1+z)$ will be scattered by dust concentrated in a ring located at the intersection of the sphere $R = R_{\text{sub}}$ and the paraboloid

$$t = \frac{R}{c}(1 - \mu), \quad (2-2)$$

where $\mu = \cos \theta$ (see Fig. 1). In our model, it is adequate to ignore a finite re-processing time and the radial distribution of the dust. The dust only has to survive for a time

$\sim \Delta t^{\text{OT}}$. We expect that, in practice, it will be quickly destroyed by the effects of secondary cosmic ray electrons created through electron scattering of the GRB so that the observed optical afterglow need not necessarily be subject to the same extinction as the echo.

2.3. Optical Scattering

The optical echo flux density $F_{\nu_{\text{ob}}}^{\text{E}}$, observed at frequency $\nu_{\text{ob}} = \nu(1+z)^{-1}$ is

$$F_{\nu_{\text{ob}}}^{\text{E}}(\nu_{\text{ob}}, t_{\text{ob}}) = \frac{L_{\nu}(\nu, t)}{2(1+z)^3 D_A^2} \frac{c \Delta t^{\text{OT}}}{R} \frac{d\mathcal{P}^{\text{sc}}}{d\Omega}(\nu, \mu); \quad (2-3)$$

$$0 < t_{\text{ob}} < 2R_{\text{sub}}(1+z)/c,$$

where $d\mathcal{P}^{\text{sc}}(\nu, \mu)/d\Omega$, is the probability of escape along the direction defined by angle $\theta = \cos^{-1} \mu$ for a photon of frequency ν .

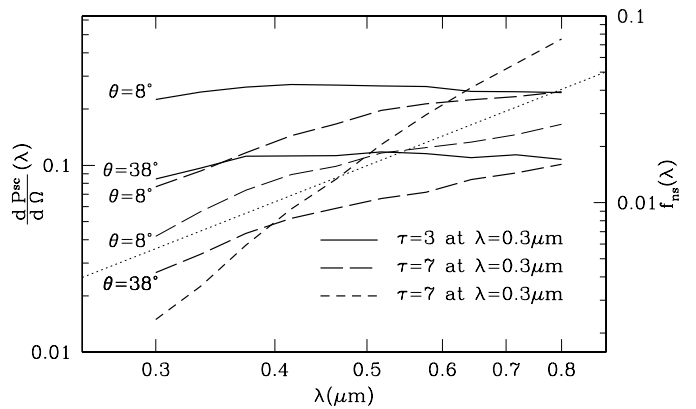


FIG. 2.— Solid and long-dashed lines show the escape probability for photons scattered by a dust slab for different values of θ and τ (as marked in the figure). For comparison, the dotted line represents an escape probability that increases the spectral index of the echo relative to the OT by 2. The thin long-dashed line shows the results computed using a different $d\sigma/d\Omega \propto 1 + 2\mu + \mu^2$ which gives similar results although it is less peaked at $\mu \sim 1$. The short-dashed line shows the fraction of photons at each wavelength, $f_{\text{ns}}(\lambda)$ which pass through the slab unscattered, approximating the escape probability at $\theta = 0$.

From Eq. (2-3) it is clear that the only time dependence comes from the angular dependence of the escape probability, $d\mathcal{P}^{\text{sc}}/d\Omega$; $F_{\nu_{\text{ob}}}^{\text{sc}}(t_{\text{ob}})$ is simply a step function for isotropic scattering. We adopt a Henyey-Greenstein function (e.g. White 1979) to describe the differential cross section for dust scattering:

$$\frac{d\sigma}{d\Omega} \propto \frac{1 - \langle \mu \rangle^2}{[1 + \langle \mu \rangle^2 - 2\langle \mu \rangle \mu]^{3/2}}, \quad (2-4)$$

with $\langle \mu \rangle = 0.5$ (Draine & Lee 1984). We then use Eq. (2-4) to compute $d\mathcal{P}^{\text{sc}}(\lambda, \mu)/d\Omega$ numerically for a slab-like dust cloud. The results for different observer angles (w.r.t. to the slab normal vector) and two different values of the total extinction, $\tau = \tau_{\text{abs}} + \tau_{\text{sc}}$ (measured at $\lambda = 0.3\ \mu\text{m}$) are shown in Fig. 2. The differential escape probability is normalized so that the integral $\int_{4\pi} \frac{d\mathcal{P}^{\text{sc}}}{d\Omega}(\lambda, \mu) d\Omega$ is equal to the escape probability from the dust cloud. Fig. 2 shows that at low optical depth $\tau_{0.3} \equiv \tau(0.3\ \mu\text{m}) \lesssim 3$, the echo should have a similar color to the OT whereas at

larger optical depth, the echo will be much redder due to absorption.

To illustrate that our calculation of the escape probability is not overly simplified (though it ignores wavelength dependence of the functional form for $d\sigma/d\Omega$, (White 1979) in Fig. 2 we show one curve (thin long-dashed line) computed using $d\sigma/d\Omega \propto 1 + 2\mu + \mu^2$. This expression gives the same value of $\langle\mu\rangle$ but is less strongly peaked at $\mu = 1$ than Eq. (2-4). The resulting $d\mathcal{P}^{\text{sc}}(\lambda, \mu)/d\Omega$ is very similar to what we use in our calculations.

The angular dependence of the escape probability is exhibited in Fig. 3 for a dust cloud with $\tau_{0.3} = 7$ and three values of the incident photon wavelength. Note that $d\mathcal{P}^{\text{sc}}(\mu)/d\Omega$ remains relatively flat for $\theta \lesssim \theta_{\text{sc}} \sim 20^\circ$ and decreases exponentially at larger angles.

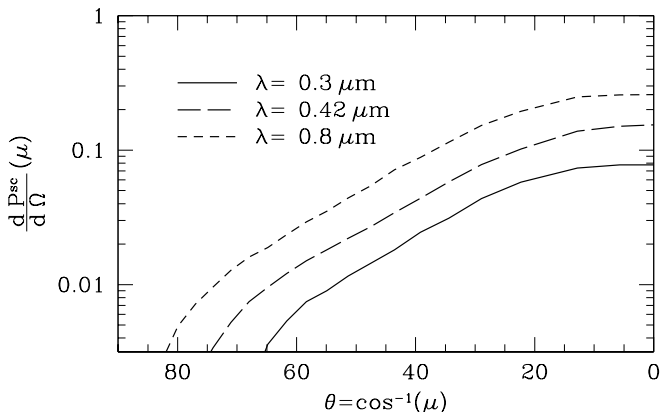


FIG. 3.— The differential escape probability is plotted as a function of θ for a dust cloud with the optical depth for extinction $\tau_{0.3} = 7$. The results are shown for three different values of the incident photon wavelength.

2.4. Infrared Echo

Hot dust will also emit an isotropic infrared echo due to thermal emission from dust at the rapid sublimation temperature ~ 2300 K, peaking at an observed wavelength $\lambda \sim 2(1+z)\mu\text{m}$. Waxman & Draine (1999) argue that only the photons in the $1 - 7.5$ eV range will contribute to dust heating. For $\tau_{0.3} \sim 7$ the absorption efficiency for photons in this energy range is > 0.8 ; and moreover, such photons are likely to carry a considerable fraction of the total OT emission. Therefore the integrated infrared flux is

$$F_{\text{IR}}^{\text{E}} = \frac{L\Delta t^{\text{OT}} c}{8\pi D_{\text{A}}^2 R} \frac{1}{(1+z)^4}. \quad (2-5)$$

3. COMPARISON WITH OBSERVATIONS

3.1. OT-Echo-Redshift Relations

Adopting our simple model of dust scattering, Eqs. (2-1, 2-2) allow us to relate the sublimation radius and OT power, $10^{47} L_{47} \text{ erg s}^{-1}$, to the observed echo delay, $t_{\text{ob}}^{\text{E}} \equiv 10^6 t_{\text{ob},6}^{\text{E}}$ s.

$$R_{\text{sub}} \sim 0.2 C_1^{-1} C_2^{-1} t_{\text{ob},6}^{\text{E}} (1+z)^{-1} \text{ pc}, \quad (3-1)$$

$$L_{47} \sim 0.03 (1+z)^{-2} C_1^{-2} C_2^{-2} (t_{\text{ob},6}^{\text{E}})^2, \quad (3-2)$$

where $C_1 = (1-\mu)/0.06$ allows for beaming or characteristic scattering angles different from 20° , and $C_2 = R/R_{\text{sub}}$ should be used if the dust is located beyond R_{sub} .

For simplicity, we now suppose that the spectral index of the OT is $\alpha \sim 1$. This is quite close to the spectral index of the observed afterglows. We can then use Eqs(2-3) to relate the R-band ($0.65\mu\text{m}$) echo flux density to the escape probability

$$F_{\nu}^{\text{E}}[0.65\mu\text{m}] \sim 0.4 \frac{d\mathcal{P}^{\text{sc}}}{d\Omega} \left(\frac{t_{\text{ob},6}^{\text{E}} \Delta t_{\text{ob},3}^{\text{OT}}}{C_1 C_2^2} \right) \times \left(\frac{D_{\text{A}}}{1.5\text{Gpc}} \right)^{-2} (1+z)^{-6} \mu\text{Jy}, \quad (3-3)$$

where the observed duration of the optical transient is $10^3 \Delta t_{\text{ob},3}^{\text{OT}}$ s. Note the strong dependence on redshift which implies that accurate measurements of both the optical transient and the echo flux could lead to a fairly precise redshift prediction.

The ratios of the optical transient flux density, $F_{\nu_{\text{ob}}}^{\text{OT}} = L_{\nu} f_{\text{ns}} (4\pi)^{-1} D_{\text{A}}^{-2} (1+z)^{-3}$, and infrared echo flux density to the optical echo flux density are likewise given by

$$\frac{F_{\nu}^{\text{OT}}[0.65\mu\text{m}]}{F_{\nu}^{\text{E}}[0.65\mu\text{m}]} \sim 3000 \left(\frac{f_{\text{ns}}}{C_1 d\mathcal{P}^{\text{sc}}/d\Omega} \right) \left(\frac{t_{\text{ob},6}^{\text{E}}}{\Delta t_{\text{ob},3}^{\text{OT}}} \right), \quad (3-4)$$

$$\frac{F_{\nu}^{\text{E}}[2(1+z)\mu\text{m}]}{F_{\nu}^{\text{E}}[0.65\mu\text{m}]} \sim 0.5 \left(\frac{d\mathcal{P}^{\text{sc}}}{d\Omega} \right)^{-1} (1+z), \quad (3-5)$$

where f_{ns} is the fraction of incident OT photons, emerging unscattered from the dust cloud.

3.2. GRB 980326

For GRB 980326, an excess R flux $F_{\nu_{\text{ob}}}^{\text{E}}[0.65\mu\text{m}] \sim 0.4\mu\text{Jy}$ was measured a time $t_{\text{ob}}^{\text{E}} \sim 20$ d (Bloom et al. 1999). If we make the simplest assumptions, $a_{-1} \sim Q_{\text{abs}} \sim C_1 \sim C_2 \sim 1$, then $R_{\text{sub}} \sim 0.3(1+z)^{-1}\text{pc}$ and $L \sim 9 \times 10^{45} (1+z)^{-2} \text{ erg s}^{-1}$. Comparing the reported spectral slope, $\alpha \sim 2.8$ of the putative echo to that of the afterglow ($\alpha \sim 0.8$), we estimate that $\tau_{0.3} \sim 7$ (cf Fig. 2). This, in turn, implies that $d\mathcal{P}^{\text{sc}}/d\Omega$ in the observed R band $\sim 0.2(1+z)^{-1}$ and $f_{\text{ns}} \sim 0.05(1+z)^{-4}$ (see Fig. 2). We can then use Eq.(3-3) to deduce that $\Delta t_{\text{ob},3}^{\text{OT}} \sim 3(1+z)^7$ and $F_{\nu_{\text{ob}}}^{\text{OT}}[0.65\mu\text{m}] \sim 200(1+z)^{-10} \mu\text{Jy}$. If $z \sim 0.4$, then the energy associated with the first optical measurement of the afterglow ($F_{\nu_{\text{ob}}}^{\text{OT}}[0.65\mu\text{m}] \sim 10 \mu\text{Jy}$ after 0.5 d), suffices to account for the observed excess after 20 d as a dust echo. If $z > 0.4$, then the optical transient would have had to be present and create a larger fluence at earlier times. This is not unreasonable as the OT flux was measured to satisfy $F^{\text{OT}} \propto t^{-2}$. In view of the large number of simplifying assumptions that we have made, this estimate can only be regarded as illustrative. However it suffices to demonstrate that dust scattering is consistent with all of the available data.

3.3. GRB 970228

A somewhat similar story can be told for GRB 970228, where the redshift, $z = 0.695$, is known (Djorgovski et al. 1999). The earliest R-band measurement is $\sim 30\mu\text{Jy}$ 0.7 d after the GRB; and after ~ 30 d there red excess flux $\sim 0.3\mu\text{Jy}$ was observed, with the spectral slope ($\alpha \sim 3.0$) very similar to that seen in GRB 980326 (Galama et al.

1999). For this object, again, within the uncertainties, the fluence measured in the first stages of the optical transient is sufficient to account for the energy in the optical excess.

3.4. Dust Origin

In both examples above, the mass of dust required to produce an optical depth $\tau_{0.3} \sim 7$ with our simplest assumptions and assuming that it is spherically symmetrically distributed with respect to the GRB is $\sim 0.1 M_{\odot}$. This amount of dust could form in an expanding high-metallicity wind associated with an earlier stage in the evolution of the GRB progenitor as we have assumed in our simple model. Alternatively the dust might be associated with a molecular cloud if GRBs are associated with massive star formation or a molecular torus should they be located in obscured galactic nuclei.

4. DISCUSSION

In this letter we present an alternative explanation for the reddened excess emission observed in GRB 970228 and GRB 980326, which we attribute to dust scattering of the early-time, afterglow emission. This scenario is predictive enough to be confirmed or ruled out with observations of future GRBs. In particular, in contrast to the supernova explanation (Bloom et al. 1999; Galama et al. 1999; Reichart 1999), if the excess emission is due to dust scattering, then its properties will depend on the luminosity of the optical transient. HETE II (<http://space.mit.edu/HETE/>) scheduled to be launched in early 2000 and Swift (<http://swift.gsfc.nasa.gov/homepage.html>), scheduled for 2003, should provide real-time localization of GRB X-ray afterglows with sufficient precision to permit faster follow-up and better measurements of its total fluence. Infrared observations may discover the expected thermal emission from hot sublimating dust (*cf* Waxman & Draine 1999). In fact dust emission might be the correct explanation for the “near-IR” bump seen in the spectrum of the GRB 991216 afterglow (Frail et al. 2000). Note that as

most GRBs are at redshifts $\gtrsim 0.5$, $3 \mu\text{m}$, (as opposed to the more common $2 \mu\text{m}$) photometry may be necessary to see this emission.

In those GRBs, where it is also possible to measure a redshift, the the simplest model of dust-scattering is over-constrained and therefore refutable. Beaming and dust inhomogeneity introduce additional uncertainty but such models may also be excludable. For example, if ROTSE (Akerlof et al. 1999) were to detect another optical flash in a GRB as luminous as that seen in GRB 990123, which had an isotropic luminosity $L \sim 10^{51} \text{ erg s}^{-1}$, then dust should be physically sublimed out to a distance $R_{\text{sub}} \sim 100 \text{ pc}$ along the line of sight. Unreasonably large beaming would then be required to explain a dust echo with a delay of only a few weeks. Alternatively, if the radio light curve in an afterglow tracked the optical light curve, then this would be incompatible with both dust scattering and a supernova.

A further prediction of the dust echo model is that, unless the dust and OT are both arranged axisymmetrically with respect to the line of sight, we expect there to be linear polarization associated with dust echos and this may be measurable in bright examples. (1.7 percent polarization has been reported in the optical transient associated with GRB 990510 by Covino et al. (1999) but this is unlikely to be due to scattering.)

In conclusion, we have demonstrated that dust scattering can account for the excess optical emission observed in the afterglows of two GRBs as an alternative to an underlying supernova explosion. Future observations should be able to rule out or confirm this explanation.

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