DELAYED X-RAY AFTERGLOWS FROM OBSCURED GAMMA-RAY BURSTS IN STAR-FORMING REGIONS

PETER MÉSZÁROS1,2,3 AND ANDREI GRUZINOV2

Received 2000 July 18; accepted 2000 September 7; published 2000 October 18

ABSTRACT

For gamma-ray bursts occurring in dense star-forming regions, the X-ray afterglow behavior minutes to days after the trigger may be dominated by the small-angle scattering of the prompt X-ray emission off dust grains. We give a simple illustrative model for the X-ray light curves at different X-ray energies and discuss possible implications. A bump followed by a steeper decay in soft X-rays is predicted for bursts that are heavily obscured in the optical.

Subject headings: gamma rays: bursts — radiation mechanisms: thermal

1. INTRODUCTION

In many of the gamma-ray bursts (GRBs) for which afterglows have been detected, most of the X-ray fluence is emitted during the first minute (e.g., Costa 1999; Piro 2000; van Paradijs, Kouveliotou, & Wijers 2000), with the afterglow X-ray emission representing a fraction \( \lesssim 0.5 \) of the total. For a GRB in a large star-forming region, a significant fraction of the prompt X-ray emission will be scattered by dust grains. Since the dust grains scatter the X-rays by a small angle, time delays of the scattered X-rays will be small (minutes to days, depending on the X-ray energy and the grain size). If the X-ray–scattering opacity is substantial, the softer part of the X-ray afterglow on the above timescales will be dominated by the dust scattering, with the direct X-ray emission from the blast wave being weaker. This intermediate X-ray light curve will then generally be steeper than the original unscattered afterglow but that the gamma rays should be able to penetrate through. However, the behavior of the X-ray afterglow will be dependent on the specific energy band being considered.

At X-ray optical depths of less than a few, dust grains of size \( a \) will scatter X-rays of energy \( \epsilon \) by an angle \( \theta \sim 0.2 \lambda/a \), where \( \lambda \) is the X-ray wavelength [Overbeck 1965, using \( x = 2\pi(a/\lambda)\theta \) after correction for a misprint; see, e.g., Alcock & Hatchett 1978]. We parameterize this as

\[
\theta(\epsilon) = 4.13 \times 10^{-3} \left( \frac{a}{0.06 \ \mu m} \right)^{-1} \left( \frac{\epsilon}{1 \ \text{keV}} \right)^{-1}. \tag{3}
\]

The corresponding time lag is \( t \sim R \theta^2/c \), or

\[
t(\epsilon) \sim 8.8 \times 10^4 \left( \frac{a}{0.06 \ \mu m} \right)^{-2} \left( \frac{\epsilon}{1 \ \text{keV}} \right)^{-2} \left( \frac{R}{100 \ \text{pc}} \right). \tag{4}
\]

The X-ray telescope\(^4\) on the Swift afterglow space mission, scheduled to be launched in 2004, will be sensitive over an energy range of \( 0.2 \leq \epsilon \leq 10 \ \text{keV} \), corresponding to GRB rest-frame energies of 0.5–25 keV for a redshift \( z = 1.5 \). Let us consider the dust contribution at several GRB-frame X-ray energies. In what follows, when specific numerical quantities are quoted, we have normalized to values of \( a = 0.06 \ \mu m \) and \( R = 100 \ \text{pc} \), while when determining functional dependences, we integrate over a grain size distribution.

At 10 keV, the X-ray optical depth given by equation (2) is much less than unity, so the X-ray afterglow is not affected by the dust scattering. The light curve will then just be the usual

\[
\tau(\epsilon) = 3 \left( \frac{\epsilon}{1 \ \text{keV}} \right)^{-2}. \tag{2}
\]

The last two assumptions are adopted from the interpretation of the dust-grain–scattering observations given by Mitsuda et al. (1990). Of course, there is no reason to believe that the dust in a distant GRB host galaxy will be similar to the dust here. We just use these assumptions as a nominal example.

It follows from the first assumption that a GRB going off into such a star-forming region will have no detectable optical afterglow but that the gamma rays should be able to penetrate through. However, the behavior of the X-ray afterglow will be dependent on the specific energy band being considered.

For numerical estimates, we assume that (1) visual extinction is \( \sim 10 \), (2) X-rays are scattered preferentially by those dust grains whose size is in the range of \( a \sim 0.06 \ \mu m \), and (3) the dust-scattering optical depth at the X-ray energy \( \epsilon \) is

\[
\theta(\epsilon) = 4.13 \times 10^{-3} \left( \frac{a}{0.06 \ \mu m} \right)^{-1} \left( \frac{\epsilon}{1 \ \text{keV}} \right)^{-1}. \tag{3}
\]

The corresponding time lag is \( t \sim R \theta^2/c \), or

\[
t(\epsilon) \sim 8.8 \times 10^4 \left( \frac{a}{0.06 \ \mu m} \right)^{-2} \left( \frac{\epsilon}{1 \ \text{keV}} \right)^{-2} \left( \frac{R}{100 \ \text{pc}} \right). \tag{4}
\]

The X-ray telescope\(^4\) on the Swift afterglow space mission, scheduled to be launched in 2004, will be sensitive over an energy range of \( 0.2 \leq \epsilon \leq 10 \ \text{keV} \), corresponding to GRB rest-frame energies of 0.5–25 keV for a redshift \( z = 1.5 \). Let us consider the dust contribution at several GRB-frame X-ray energies. In what follows, when specific numerical quantities are quoted, we have normalized to values of \( a = 0.06 \ \mu m \) and \( R = 100 \ \text{pc} \), while when determining functional dependences, we integrate over a grain size distribution.

At 10 keV, the X-ray optical depth given by equation (2) is much less than unity, so the X-ray afterglow is not affected by the dust scattering. The light curve will then just be the usual

\[
\tau(\epsilon) = 3 \left( \frac{\epsilon}{1 \ \text{keV}} \right)^{-2}. \tag{2}
\]
unscattered time-dependent X-ray afterglow, which in this example is parameterized through equation (1).

At 3 keV, the optical depth is \( \tau \sim 0.3 \). The time lag, equation (4), is \( t \sim 10^4 \) s. Since the total fluence is \( f \sim 1 \) for \( F_0 \sim 500 \) s, the scattered flux is \( F_\tau \sim \tau f t \sim 0.01 \). The unscattered flux \( F_0 \) at \( 10^4 \) s is given by equation (1); i.e., \( F_0 \sim 3 \times 10^{-3} \). Thus, scattering has only a minor influence on the afterglow.

At 2 keV, the optical depth is \( \tau \sim 1 \). The time lag is \( t \sim 2 \times 10^4 \) s. The scattered flux is \( F_\tau \sim \tau f t \sim 0.03 \). The unscattered flux at \( 2 \times 10^4 \) s is \( F_0 \sim 10^{-3} \). In the time interval from hours to weeks, the dust scattering dominates the afterglow, and, as shown in Figure 1, the afterglow is approximately a power law \( F \sim \tau f t \). This is because dust grains of radius \( a < 0.06 \) \( \mu m \) will scatter the prompt emission with longer time lags, \( t \propto a^{-3} \), and with smaller optical depths \( \tau \). To calculate \( \tau \), we take a standard dust grain size distribution in which the number of grains of size of order \( a \) is proportional to \( a^{-2.5} \) (Mathis, Rumpl, & Nordsieck 1977). For a scattering cross section proportional to \( a^4 \) (Overbeek 1965), the optical depth is \( \tau \propto a^{1.5} \propto t^{-0.75} \), so the flux \( F \propto t^{1.75} \).

At 1 keV, the optical depth is \( \sim 3 \), and the dust grain scattering dominates the afterglow at \( t > 10 \) minutes. Multiple scatterings will be important, with the net deflection angle being, in the small-angle deflection regime, \( \theta \sim N_{\text{scatt}}^{-2} \theta(\epsilon) \simeq \tau^{1/2} \theta(\epsilon) \), so \( \epsilon \), the time delay is \( t(\epsilon) \sim \theta^2(R/2c) \sim \epsilon^{-2} \). At early times, this decreases the ratio of the scattered to the unscattered flux, compared with the values in the single scattering regime at 2 keV, and it increases the time after which the scattered flux becomes dominant, the late time decay having the same time exponent of \( -1.75 \).

3. DISCUSSION

The specific example that we have described shows that highly obscured star-forming regions should lead to specific signatures in the X-ray light curve of gamma-ray bursts occurring in them. This consists of a secondary flattening or bump in the light curve at X-ray energies \( \epsilon \sim 2-3 \) keV. A physically distinct but related effect is that of X-ray echoes from scattering by electrons (Madau, Blandford, & Rees 2000); at keV energies, this effect would be independent of energy, and hence easily distinguishable from the dust-scattering effects discussed here, and is very sensitive to energy. Depending on the size and dust column density of the region, this bump occurs hours to days after the initial "canonical" X-ray decay has been going on, followed by a steeper \( F_\tau \propto t^{-1.75} \) decay. At lower energies (e.g., in the 0.2-0.5 keV range), the X-ray bump in the light curve should appear at increasingly later times and should contribute a decreasing fraction of the total energy.

The presence of this X-ray signature is expected to be associated with bursts that do not produce a detectable transient at optical wavelengths. There are at least three bursts so far for which an X-ray decay index is known and an optical transient (OT) was not detected: GRB 970204, 970828, and 991214. The X-ray decay indices of these were \(-1.4, -1.56, \) and \(-1.00 \), based on GCN notices.\(^5\) The third is clearly a canonical decay and should be the unscattered component, but the other two could be the scattered component, considering the uncertainties in the grain size distribution and cross sections that determine the decay rate. There is a larger number of bursts for which an X-ray afterglow was reported, while an OT was not found. However, since optical observations first require an X-ray position, which so far has been possible only after hours of delay and with arcminute accuracy, there is currently a possible bias against finding OTs. Stronger constraints will have to await the faster coordinate alerts and smaller X-ray error circles expected from dedicated GRB afterglow missions such as HETE-2 and Swift.

An infrared source is expected to be associated with such obscured, X-ray peculiar GRBs since the dust will reradiate the UV and soft X-ray radiation of the absorbed source. Thermal reradiation and scattering outside the sublimation radius are expected to cause delayed IR emission even when the OT is only partially absorbed (Waxman & Draine 2000; Esin & Blandford 2000), and the same is expected here, except for the OT being completely obscured. As a numerical example, for an isotropic equivalent total burst energy \( E \sim 10^{53} \) ergs at a redshift \( z \sim 1 \), the normalization of the X-ray flux for the burst of Figure 1 would be \( F_\tau \sim 10^{-9} \) ergs \( cm^{-2} s^{-1} keV^{-1} \) for \( t \leq 100 \) s, in the usual range of X-ray afterglow fluxes detected by BeppoSAX (Costa 1999). The dust reradiation occurs beyond the sublimation radius \( R_s \sim 10L_{15}^{1/2} \) pc at wavelengths \( \lambda \sim 2(1+z) \mu m \), where \( 10^{50}L_{49}^{1/2} \) ergs \( s^{-1} \) is the early UV component of burst afterglow (Waxman & Draine 2000). The time delay associated with the reradiated flux is \( \tau_{\text{IR}} \sim (R_s/2c)\theta^2 \), where \( \theta_{\text{IR}} \sim 10^{-3} \theta_{-1} \) is a typical collimation half-angle of the burst radiation. At \( z \sim 1 \), the corresponding infrared flux at 2.2 \( \mu m \) would be \( F_{\text{IR}} \sim L_{15}^{1/2} \theta^2/[4\pi D_L^2(R_s/2c)\theta^2] \sim 0.3L_{15}^{1/2} \) \( \mu d \), independent of \( \theta_p \) or \( m_1 \sim 23.3 \). Compared with Vega, approximately constant for a time \( \tau_{\text{IR}} \sim 5 \times 10^5 \theta_{-1}^{1/2} L_{49}^{1/2} \) s. The IR flux of the host galaxy at that redshift could exceed this value, but 8 m-class telescopes in good seeing conditions or with adaptive optics would resolve the host galaxy, facilitating detection of the pointlike IR afterglow. If the ratio of X-ray to IR fluxes can be calibrated for a sample of sources at \( z \sim 1 \), such gamma-ray-detected GRBs with anomalous X-ray afterglow behavior and no OT may be used as tracers of massive stellar collapses. It may thus be possible to detect star-forming regions out to redshifts larger than those detectable with optical or infrared techniques since typical GRB gamma-

\(^5\) Available at http://www.aip.de:8080/elcg/irbgen.html by J. Greiner 2000.
ray and X-ray fluxes can, in principle, be measured out to $z \sim 10–15$.

We thank Andrew Blain, Bruce Draine, Masataka Fukugita, David Hogg, Kevin Hurley, Richard McMahon, Martin Rees, and Eli Waxman for useful discussions. P. M. was supported by NASA grant NAG5-9192, the Guggenheim Foundation, the Sackler Foundation, and the Institute for Advanced Study. A. G. was supported by the W. M. Keck Foundation and NSF grant PHY 95-13835.

REFERENCES

Alcock, C., & Hatchett, S. 1978, ApJ, 222, 456
Costa, E. 1999, A&AS, 138, 425
Esin, A. A., & Blandford, R. 2000, ApJ, 534, L151
Madau, P., Blandford, R. D., & Rees, M. J. 2000, ApJ, 541, 712
Mathis, J. S., Rumpl, W., & Nordsieck, K. H. 1977, ApJ, 217, 425
Mitsuda, K., Takeshima, T., Kii, T., & Kawai, N. 1990, ApJ, 353, 480

Overbeck, J. W. 1965, ApJ, 141, 864
Piro, L. 2000, preprint (astro-ph/0001436)
van Paradijs, J., Kouveliotou, C., & Wijers, R. A. M. J. 2000, ARA&A, in press
Waxman, E., & Draine, B. T. 2000, ApJ, 537, 796