GRB 990123: THE CASE FOR SATURATED COMPTONIZATION

E. P. Liang, A. Crider, M. Böttcher, and I. A. Smith
Department of Space Physics and Astronomy, Rice University, 6100 South Main, Houston, TX 77005-1892

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ABSTRACT

We find that the optical magnitudes of GRB 990123 observed by the Robotic Optical Transient Search Experiment move in tandem with the magnitudes extrapolated from the simultaneous BATSE spectra, strongly suggesting that the optical, X-ray, and gamma-ray photons originate from a single source. We then show that the broadband optical–gamma-ray spectra can be naturally fit by the saturated Compton model. We also derive the parameters of the Compton emitting shell from first principles.

Subject headings: gamma rays: bursts — gamma rays: observations

1. INTRODUCTION

The recent simultaneous detection of optical (Akerloff et al. 1999), X-ray (Feroci et al. 1999), and gamma-ray photons (Kippen et al. 1999) from GRB 990123 during the burst provides the first broadband multiwavelength characterization of the burst spectrum and evolution. Here we show that a direct correlation exists between the time-varying gamma-ray spectral shape and the prompt optical emission. This combined with the unique signatures of the time-resolved spectra of GRB 990123 strongly supports earlier predictions of the saturated Comptonization model (Liang et al. 1997; Liang 1997). Contrary to other suggestions (Galama et al. 1999; Sari & Piran 1999; Briggs et al. 1999), we find that the entire continuum from optical to gamma rays can be generated from a single source of leptons (electrons and pairs). The optical flux only appears to lag the gamma-ray flux because of the high initial Thomson depth of the plasma. Once the plasma has completely thinned out, the late-time afterglow behavior of our model is the same as in standard models based on the Blandford-McKee (1976) solution.

2. DATA ANALYSIS AND INTERPRETATION

To generate the gamma-ray spectra of GRB 990123 during the Robotic Optical Transient Search Experiment (ROTSE) observations, we fit the public BATSE data (SHER/SHER+DISCSP1; see Preece et al. 1996) with the Band et al. (1993) gamma-ray burst (GRB) function, which is a four-parameter model that smoothly joins two power laws. Although the gamma-ray flux time history initially appears to be unrelated to the earliest observed optical evolution (Briggs et al. 1999), a V-band extrapolation of the Band GRB function fit to the BATSE data shows that it varies in tandem with the ROTSE fluxes (see Fig. 1). This suggests that the gamma-ray and optical emission likely arise from the same source. We stress that it is essential to consider the time-varying shape of the GRB continuum and not merely the magnitude of the gamma-ray flux.

Examination of the MER/CONT data during the first ROTSE time bin, which includes approximately 10 times as many counts as the SHER/SHERB data, shows an upturn in the lowest energy channel, inconsistent with the Band GRB function fit by 6.7 σ. Inclusion of the SD discriminator channel corroborates the MER/CONT upturn and is inconsistent with the Band GRB function fit by 3.7 σ. (We also find the discriminator channel data to be in rough agreement with the peak flux reported by BeppoSAX [Feroci et al. 1999], assuming that a simple power-law spectrum exists between the lowest MER channel and the ROTSE observations.) Fitting the MER+DISCSP1 spectra with a function that allows a low-energy upturn, such as the cold Compton attenuation function (Brainerd 1994; Brainerd et al. 1998), drastically improves the χ² of the fit by 143 without including extra degrees of freedom. Such upturns have been observed in many previous bursts (Fenimore et al. 1982; Preece et al. 1996; Brainerd et al. 1998; Crider et al. 1999b). As we describe below, however, while the Compton attenuation model can mimic the observed gamma-ray spectra, it cannot produce the observed X-rays seen by BeppoSAX. We turn instead to inverse Comptonization spectra, which naturally produce the “terrace” spectral shape seen by BATSE, the X-ray flux seen by BeppoSAX, and the optical flux seen by ROTSE. In Figure 2, we plot the three BATSE spectra deconvolved with inverse Comptonization spectra (see § 3), as well as the simultaneous ROTSE optical measurements.

The popular optically thin synchrotron shock model for the relativistic blast wave (e.g., Mészáros & Rees 1993; Piran & Shemi 1993; Katz 1994; Tavani 1996) can only produce the high-energy spectral break provided that the slope below the break is less than $-\frac{2}{3}$. It cannot produce the additional low-energy upturn. To maintain the optically thin synchrotron shock model, it has been proposed that the optical emission comes from a separate component (Sari & Piran 1999). However, as we see in Figure 1, a separate optical source is unnecessary and artificial given the tandem movement of the optical flux and the gamma-ray extrapolation. Moreover, the BATSE data alone in Figure 2a is enough to establish the terrace shape. A separate problem with the synchrotron shock model is that it violates the observed spectral evolution seen in many bursts (Crider et al. 1997; Preece et al. 1998). A terrace can in principle be produced also by the Compton attenuation of a power-law spectrum by cold intervening material (Brainerd et al. 1998; Brainerd 1994; Liang & Kargatis 1994). However, the extremely high column density ($N_H > 10^{25} \text{ cm}^{-2}$) required, even for subsolar abundances of metals, would have completely absorbed the X-rays below 10 keV, contrary to the BeppoSAX results. For GRB 990123, the required extinction would also be inconsistent with the blue color of the optical source. Thus, the broadband spectra of Figure 2 are inconsistent with the cold Compton attenuation model.
Fig. 1.—Gamma-ray (24–1800 keV) and optical prompt emission of GRB 990123. The gamma-ray photon flux is calculated from the MER data fit using a Band et al. (1993) GRB function with $\beta$ fixed to $-3$ (as found by OSSE). Extrapolating a Band GRB function fit to the SHER/SHERB data during each ROTSE time bin gives $V$ magnitudes (squares). This shows a similar evolution to the ROTSE observations (circles). There are minor differences in the time intervals used because of binning constraints.

The terrace-shaped continuum, such as that in Figure 2a, is a natural consequence and unique signature of saturated Comptonization (Rybicki & Lightman 1979; Sunyaev & Titarchuk 1980; Fenimore et al. 1982) and was predicted 2 years ago when this model was developed to explain other details of GRB spectral evolution (Liang et al. 1997; Liang 1997). In this picture, the GRB phase of a burst corresponds to the time when the relativistically expanding shell is still very dense and Thomson thick ($t_\tau > 1$). The X- and gamma-rays are produced by multiple Compton upscattering of self-emitted synchrotron and bremsstrahlung soft photons (peaking below the IR; Liang 1997). When the Thomson depth is very high a Wien peak emerges, producing a high-energy spectral break (Rybicki & Lightman 1979). At low energies, the spectrum turns up with a power law of slope $\leq -1$, producing the characteristic terrace shape (Figs. 2a and 3a). The low-energy upturn usually occurs approximately 1–2 orders of magnitude below the high-energy break (Rybicki & Lightman 1979; Sunyaev & Titarchuk 1980; Liang & Nolan 1984). This low-energy upturn is caused by the competition between spatial and energy diffusion in a medium with volume injection of soft photons.

In the Compton cooling model (Liang et al. 1997), the photon diffusion is assumed to be faster than the observable burst evolution timescales. For example, if we use a Compton diffusion time of $\sim 1$ s, then the $t_\tau$ and $\Gamma$ values from Table 1 require that the comoving thickness $H$ be $\geq 10^{12}$ cm. This limit is consistent with the thickness of internal shocked shells based on the colliding fireball shells in the late matter-dominated phase ($H < 10^{14}$ cm, eq. [15] from Piran 1994). Details of such

Fig. 2.—BATSE spectra of GRB 990123 coincident with the first three ROTSE observations. The dashed curves show the extrapolations of the Band (1993) GRB function fits to the gamma-ray data. The histograms show our Monte Carlo inverse Comptonization model spectra. The parameters used in each simulation are (a) $t_\tau = 20, \xi = 0.5, T/T_{\rm{c}}(1+z) = 80$ keV, $\xi = 3, B = 10^5$ G, $p = 3$; (b) same parameters, except $t_\tau = 6$ and $p = 6$; (c) same parameters, except $t_\tau = 8.4$ and $p = 6$.
A thin uniform shell of thermal plus nonthermal leptons Compton upscatter self-emitted synchrotron and bremsstrahlung photons. The output is then Lorentz boosted and cosmologically redshifted to the observer frame to match the data. Hence, the shell parameters are dependent on the bulk Lorentz factor, which must be constrained from other physical self-consistency considerations (e.g., pulse rise times; Liang 1997). For a given $\Gamma$, the Comptonized spectrum is then specified by the (comoving frame) magnetic field $B$, Thomson depth $\tau_\gamma$, thermal lepton temperature $T$, nonthermal lepton fraction $\xi$, and nonthermal power-law index $p$. We have used an upper Lorentz factor cutoff of $10^6$ in the lepton distribution, which is adequate for modeling spectra up through the COMPTEL energy range.

Because of the large number of model parameters, the currently available spectral data are not very constraining on the model parameter space. Even if we had more data points (e.g., from BeppoSAX, Oriented Scintillation Spectrometer Experiment [OSSE], and COMPTEL), computational limitations prohibit us from directly searching for the best-fit model spectrum using $\chi^2$ minimization techniques. Hence, the model fits presented here in Figure 2 are only meant to demonstrate a proof of principle, showing the resulting terrace shape and its evolution. Parameters of the sample model are listed in the caption of Figure 2. Even with such crude fits, we can see evidence of Thomson thinning and steepening of the nonthermal lepton index.

In Figure 3 we show examples of different Monte Carlo Compton spectra in the emitter frame to illustrate how the spectral shape varies with the different input parameters. We see that the prominence of the terrace is primarily correlated with the Thomson depth.

### 4. COMPTON SHELL PARAMETERS

We have deconvolved the time-resolved BATSE spectra for the whole burst using the Band et al. (1993) GRB function. The BATSE spectral evolution data allows us to derive the $E_\gamma$-fluence decay constant $\Phi_\gamma$ (Liang & Kargatis 1996; Cridder et al. 1999a) of each pulse. We find apparent cm-3 cm-2 for the pulses containing the three optical intervals (the intrinsic $\Phi_\gamma$ could be lower because of gravitational lensing). From this plus the pulse rise times, we can constrain from first principles the Compton ejecta shell parameters (Liang 1997), including $\Gamma$, the shell radius, total lepton mass $M_e$, and total lepton energies. These model parameters are listed in Table 1. Using these parameters, we can estimate the transition time from the free-expansion (internal shock) phase to the blast-wave (external shock) phase, which is nominally identified with the “afterglow” power law, as a function of the ISM/CBM density and ejecta proton loading. We see that the predicted transition

### TABLE 1

| Parameters of GRB Ejecta Shell Based on the Saturated Compton Model |
|---------------------------------------------------------------|
| **Parameter**                   | **Value**                                |
| Radius                        | $R = 8.5 \times 10^{16}$ cm $d\Phi_{\gamma}^{-0.65}$ |
| Bulk Lorentz factor           | $\Gamma \geq 376 d\Phi_{\gamma}^{-0.65}$    |
| Total lepton number           | $N_e = 2.7 \times 10^8 d\Phi_{\gamma}^{-0.65}$ |
| Total lepton mass             | $M_e = 2.5 \times 10^{50}$ g $d\Phi_{\gamma}^{-0.65}$ |
| Total shell mass              | $M = M_f \leq M_f [1 + 1836(n/n_f)] \leq 1837 M_f$ |
| Total bulk kinetic energy     | $MT\gamma \geq 8.5 \times 10^{50}$ ergs $d\Phi_{\gamma}^{-0.65} \Omega_{\gamma} f\Delta T_{\gamma}^{-0.65}$ |
| Blast-wave transition radius  | $R_{\text{bw}} = (3M/4\pi M_f) \leq 7.1 \times 10^{15}$ cm $d\Phi_{\gamma}^{-0.65} \Omega_{\gamma} f\Delta T_{\gamma}^{-0.65}$ |
| Blast-wave transition time    | $T_{\text{bw}} \leq (R_{\text{bw}}/2\Gamma \Delta\gamma) \leq 837 \times d\Phi_{\gamma}^{-0.65} \Omega_{\gamma} f\Delta T_{\gamma}^{-0.65} \Omega_{\gamma} f\Delta T_{\gamma}^{-0.65}$ |
time to the afterglow phase (see Table 1) is indeed consistent with the observed transition time of a few hundred seconds (Galama et al. 1999).

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