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Abstract. GRB 990123 established the existence of prompt optical emission from gamma-ray bursts (GRBs). The Livermore Optical Transient Imaging System (LOTIS) has been conducting a fully automated search for this kind of simultaneous low energy emission from GRBs since October 1996. Although LOTIS has obtained simultaneous, or near simultaneous, coverage of the error boxes obtained with BATSE, IPN, XTE, and BeppoSAX for several GRBs, image analysis resulted in only upper limits. The unique gamma-ray properties of GRB 990123, such as very large fluence (top 0.4%) and hard spectrum, complicate comparisons with more typical bursts. We scale and compare gamma-ray properties, and in some cases afterglow properties, from the best LOTIS events to those of GRB 990123 in an attempt to determine whether the prompt optical emission of this event is representative of all GRBs. Furthermore, using LOTIS upper limits in conjunction with the relativistic blast wave model, we weakly constrain the GRB and afterglow parameters such as density of the circumburster medium and bulk Lorentz factor of the ejecta.

INTRODUCTION

The ultimate reward for the Gamma-Ray Burst Coordinates Network (GCN) [1] came when the Robotic Optical Transient Search Experiment (ROTSE) detected prompt optical emission from GRB 990123 [2]. Although this discovery marks another milestone in comprehending the physics of GRBs, bright optical transients (OTs) may be the exception rather than the rule. Both LOTIS and ROTSE have unsuccessfully attempted to detect these predicted flashes on many occasions [3–8]. Although some of the non-detections may be attributed to large extinction, GRB 990123 demonstrated that the progenitor is not always obscured.

OBSERVATIONS & ANALYSIS

During more than 1100 nights of possible observations (since October 1996), LOTIS has responded to 127 GCN triggers. Of these, 68 triggers were unique GRB events; a rate of approximately one unique GRB event every 16.5 days. The quality of the LOTIS "coverage" for a given event depends on five factors: observing conditions, LOTIS response time, difference between the initial and final coordinates, size of the final error box, and the duration of the GRB. Table 1 lists 13 events for which LOTIS achieved good coverage.

First we compare GRB 990123 with the LOTIS upper limits to test whether the flux of the prompt optical emission scales with some gamma-ray property. Here and throughout the analysis we neglect extinction effects. The first row in Table 1 lists the properties of GRB 990123 [9,2]. The columns display the UTC date of the burst, the BATSE trigger number, the 64 ms and 1024 ms peak fluxes (50 - 300 keV), and the gamma-ray fluence (>20 kev) of each event. The last three columns are the scaled magnitudes,

$$m_{\rm GRB} = m_{\rm GRB990123} - 2.5\log\left(\frac{X_{\rm GRB}}{X_{\rm GRB990123}}\right), \tag{1}$$

TABLE 1. LOTIS GRB events with good coverage and predictions for the scaled magnitudes of the prompt optical emission.

Date	BATSE Trig.	F_p (64 ms) (γ cm^{-2} s^{-1})	F_p (1024 ms)	$S/10^{-7}$ (erg cm^{-2})	$m_{F;64}$	$m_{F;1024}$	m_S
990123	7343	16.96	16.41	3000	9.0	9.0	9.0
961017	5634	4.22	1.98	5.07	10.5	11.3	15.9
961220	5719	1.93	1.60	18.11	11.4	11.5	14.5
970223	6100	19.41	16.84	968	8.9	9.0	10.2
970714	6307	1.89	1.32	17.09	11.4	11.7	14.6
970919	6388	1.10	0.77	22.49	12.0	12.3	14.3
971006	6414	2.08	1.79	258	11.3	11.4	11.7
971227	6546	3.32	2.11	9.25	10.8	11.2	15.3
990129	7360	5.88	4.99	585	10.2	10.3	10.8
990308	7457	2.02	1.26	164	11.3	11.8	12.2
990316	7475	3.87	3.67	529	10.6	10.6	10.9
990413	7518	3.78	2.57	68.13	10.6	11.0	13.1
990803	7695	16.99	12.19	1230	9.0	9.3	10.0
990918	7770	5.69	3.17	25.21	10.2	10.8	14.2

where $m_{GRB990123} = 9.0$, the peak magnitude of GRB 990123, and X_{GRB} and $X_{GRB990123}$ are the peak flux or fluence values for those events.

The LOTIS sensitivity varies depending on observing conditions but in general a conservative limiting magnitude is $m \approx 11.5$ prior to March 1998 (upgrade to cooled CCD) and $m \approx 14.0$ following that date. Table 1 shows that the scaled prompt optical emission for both peak flux and fluence is often brighter than the LOTIS upper limits which suggests that these simple relationships are not valid.

Briggs *et al.* [9] show that the optical flux measured during GRB 990123 is not consistent with an extrapolation of the burst spectrum to low energies. However Liang *et al.* [10] point out that the extrapolated tails rise and fall with the optical flux. A low energy enhancement would produce an upward break which might account for the measured optical flux during GRB 990123. It is important to determine if there is a low energy upturn in the spectrum since it would establish whether or not the optical and gamma-ray photons are produced by the same electron distribution. The LOTIS upper limits can be used to constrain a low energy enhancement assuming it is common to all GRBs.

For the events listed in Table 1 we fit the gamma-ray spectra during the LOTIS observations to the Band functional form [11]. In a few cases the low energy extrapolation is near the LOTIS upper limit. The solid line in Figure 1 shows the Band fit to GRB 971006 and its extrapolation to low energies. Fits to the spectra of GRB 990123 during the first (short dash), second (dash-dot), and third

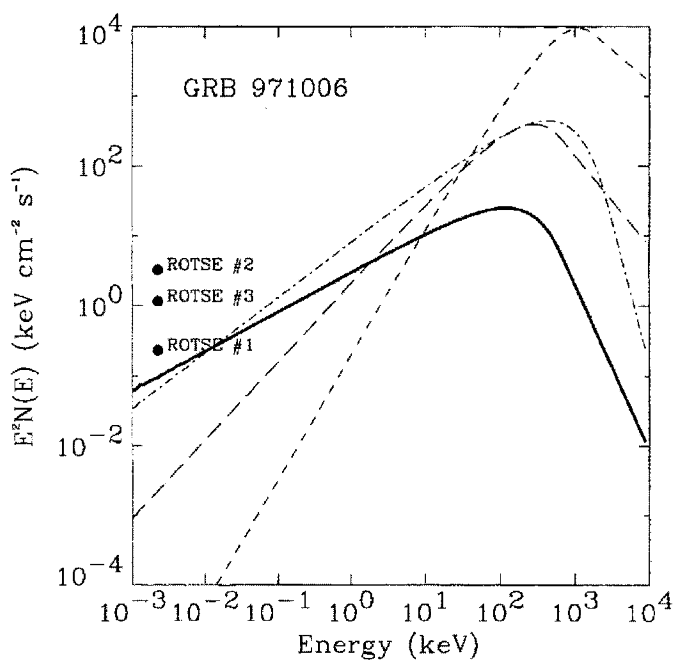

FIGURE 1. Extrapolated spectrum of GRB 971006 during the LOTIS observation and GRB 990123 during ROTSE detections.

(long dash) ROTSE observations and the corresponding ROTSE detections (filled circles) are also shown. The extrapolation of GRB 971006, predicts an $m \approx 12.4$ optical flash. Even a slight upward break in the spectrum would have produced a detectable OT. We conclude that the LOTIS upper limits support the hypothesis that the low energy emission is produced by a different electron distribution than the high energy emission.

Finally we attempt to use the LOTIS upper limits and the external reverse shock model to constrain the physical properties of the GRB blast wave. Sari and Piran [12] show that the fraction of the energy which gets emitted in the optical band depends on the values of the cooling frequency and the characteristic synchrotron frequency. For the external reverse shock these frequencies are given by

$$\nu_c = 8.8 \times 10^{15}\text{Hz}\left(\frac{\epsilon_B}{0.1}\right)^{-3/2} {E_{52}}^{-1/2} {n_1}^{-1} {t_A}^{-1/2}, \tag{2}$$

$$\nu_m = 1.2 \times 10^{14}\text{Hz}\left(\frac{\epsilon_e}{0.1}\right)^{2}\left(\frac{\epsilon_B}{0.1}\right)^{1/2}\left(\frac{\gamma_0}{300}\right)^{2} {n_1}^{1/2}, \tag{3}$$

where ϵ_e and ϵ_B are the fraction of equipartition energy in the electrons and magnetic field, E_{52} is the total energy in units of 10^{52} erg, n_1 is the density of circumburster medium in cm^{-3}, γ_0 is the initial Lorentz factor, and t_A is the duration of the emission in seconds.

Sari and Piran assume the frequency dependencies modify the fluence of a moderately strong GRB, i.e. 10^{-5} erg cm^{-2}. In this analysis we compare the afterglow

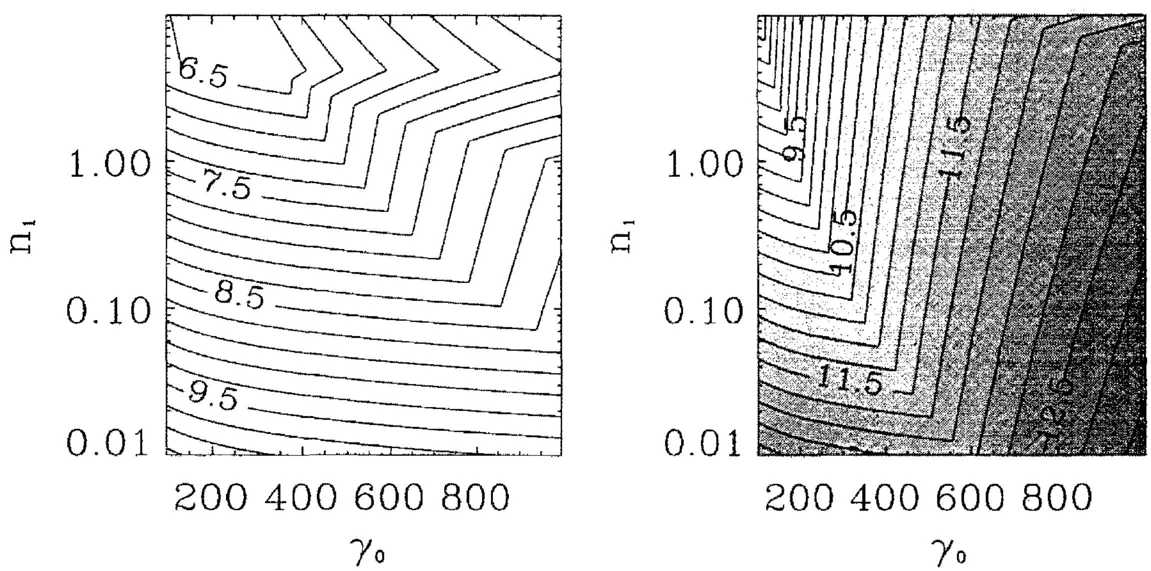

FIGURE 2. Predicted magnitude of the prompt optical flash for $E_{52} = 3.5$, $\epsilon_e = 0.12$, and $\epsilon_B = 0.089$ (left panel) and $E_{52} = 0.53$, $\epsilon_e = 0.57$, and $\epsilon_B = 0.0082$ (right panel).

properties of GRB 970508 found by Wijers and Galama [13] to those found by Granot *et al.* [14]. Therefore we use a fluence of 3.1×10^{-6} erg cm^{-2} emitted over the entire LOTIS integration time of $t_A = 10.0$ s. The index of the electron power-law distribution is set to p = 2.2.

Figure 2 shows contour plots of the predicted magnitude of the prompt OT for GRB 970508 as a function of n_1 and γ_0. GRB 970508 could not be observed by LOTIS or ROTSE since it occurred during the day. Values of $E_{52} = 3.5$, $\epsilon_e = 0.12$, and $\epsilon_B = 0.089$ from Wijers and Galama are used in the left panel and values of $E_{52} = 0.53$, $\epsilon_e = 0.57$, and $\epsilon_B = 0.0082$ from Granot *et al.* are used in the right panel. The right panel demonstrates the effect of altering the total energy and the distribution of energy to the electrons and the magnetic field. The smaller values of E_{52} and ϵ_B shift the contours to the upper left while the larger ϵ_e steepens the breaks in the contours. The increased shading corresponds to a decreasing detection probability. However for nearly all values of n_1 and γ_0 shown the predicted OT could have been detected by the upgraded LOTIS system.

Wijers and Galama find a circumburster medium density of $n_1 = 0.030$ which predicts an $m = 9.0 - 9.5$ optical flash nearly independent of the initial Lorentz factor. Granot *et al.* find a considerably higher vlaue of $n_1 = 5.3$, which predicts an $m = 8.7 - 12.4$ OT which is very dependent on the initial Lorentz factor. The LOTIS upper limits mildly favor the GRB blast wave values determined by Granot *et al.* since dim OTs are predicted over a larger range of initial Lorentz factors.

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