REAL-TIME OPTICAL FLUX LIMITS FROM GAMMA-RAY BURSTS MEASURED BY THE GAMMA-RAY OPTICAL COUNTERPART SEARCH EXPERIMENT

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ABSTRACT

The Gamma-Ray Optical Counterpart Search Experiment presents new experimental upper limits on the optical flux from gamma-ray bursts (GRBs). Our experiment consisted of a fully automated very wide-field opto-electronic detection system that imaged locations of GRBs within a few seconds of receiving trigger signals provided by BATSE’s real-time burst coordinate distribution network. The experiment acquired 3800 observing hours, recording 22 gamma-ray burst triggers within ~30 s of the start of the burst event. Some of these bursts were imaged while gamma-ray radiation was being detected by BATSE. We identified no optical counterparts associated with gamma-ray bursts among these events at the \( m_V \sim 7.0–8.3 \) sensitivity level. We find the ratio of the upper limit to the \( V \)-band optical flux, \( F_V \), to the gamma-ray fluence, \( \Phi_V \), from these data to be \( 1 \times 10^{-18} < F_V/\Phi_V < 2 \times 10^{-16} \).

Subject heading: gamma rays: bursts

1. INTRODUCTION

Cosmic gamma-ray bursts (GRBs) are arguably the most intriguing phenomena in modern high-energy astrophysics. Resolving the mystery of the origin of gamma-ray bursts will probably require the discovery of counterpart radiation in other wavebands, particularly in the optical band. At the very least, upper limits at other frequencies constrain GRB sources’ multiwavelength characteristics and thus possible emission mechanisms. It is not surprising that several near-simultaneous counterpart searches are in progress (see Hudec 1995; Hudec et al. 1995, and references therein). Here we report on the results of 2 years of operation of the Gamma-Ray Optical Counterpart Search Experiment (GROCSE).

Counterpart emission can be described as flaring, fading, or quiescent (Schaefer 1994). Flaring emission would be simultaneous with the burst observed in the gamma-ray band. Fading emission would not necessarily be present during the gamma-ray burst but would build up in intensity, then subsequently fade. One approach for observing flaring emission is to scan the sky independent of a gamma-ray detector. This is the strategy of the Ondrejov photographic network (Hudec 1993; Greiner 1992, 1995; Greiner et al. 1994; Hudec et al. 1995), and the Explosive Transient Camera (ETC; Vanderspek, Krimm, & Ricker 1994). It was also the intended strategy of the ill-fated High Energy Transient Explorer (HETE; Ricker et al. 1988). Alternatively, a detector can respond rapidly to a burst trigger from a gamma-ray instrument, catching a burst in its later phase. This approach was used by this experiment, GROCSE, and has been adopted by other operational systems as well: e.g., the BATSE-COMPTEL-NMSU network (McNamara 1996) and the Livermore Optical Transient Imaging System (LOTIS; Park 1997). Burst coordinates are currently distributed in near-real-time by the BATSE CO-ordinate Distribution Network (BACODINE; Barthelmy et al. 1994), which monitors BATSE data on board and responds to bursts by calculating and distributing preliminary burst positions.

There are no firm predictions of expected optical emission because the origin and nature of GRBs are uncertain. Schaefer’s report of optical transients on archival photographic plates (Schaefer 1981, 1984) led to a number of theoretical models that in general attempted to explain the apparent magnitudes of these optical transients. These theories included reprocessing gamma rays in a stellar companion’s atmosphere (London & Cominsky 1983; London 1984; Rappaport & Joss 1985; Melia, Rappaport, & Joss 1986; Cominsky, London, & Klein 1987) or in an accretion disk (Epstein 1985; Melia 1988). Other theories attributed optical-ultraviolet emission to processes in a neutron star magnetosphere (Liang 1985; Katz 1985; Bisnovatyi-Kogan & Illarionov 1986; Sturrock 1986; Ruderman 1987; Hartmann, Woosley, & Arons 1988; Hameury & Lasota 1989; Ho & Epstein 1989; Dermer 1990) and assumed source distances of order 100 pc. The latter theories were largely invalidated by the BATSE observations, which placed large lower distance limits and instead support Galactic halo or cosmological models. Ford & Band (1996) found by simple extrapolation of burst spectra that, at any given site, flaring emission would be observable from only a few bursts per year with \( m_V \sim 10–15 \). The brighter predicted optical fluxes result from bursts with soft gamma-ray spectra. If we instead assume the low-energy photon spectrum is \( F_V \propto E^{1/3} \), as expected for synchrotron emission from an electron distribution with a low-energy cutoff (Katz 1994; Tavani 1996a, 1996b), then the predicted distribution of optical fluxes will be shifted toward fainter magnitudes.
A number of theories suggest that fading optical emission may be observable as a result of reprocessing of burst radiation by the medium surrounding the burst source: Jennings (1983) considered Hz line radiation from resonant scattering and recombination, while Chevalier (1986), Schaefer (1987), and Katz & Jackson (1988) investigated dust scattering of radiation from an optical transient. These models predict that ionizing radiation is reprocessed to optical radiation in a manner thus far unobserved. The fading emission is proportional to the burst fluence and the density of the reprocessing region. For sufficiently large optical emission, the density must be \( n \approx 10^5 \text{ cm}^{-3} \) (Band & Hartmann 1992). These models were constructed within the paradigm of local burst sources and thus do not provide usable optical predictions, if one accepts the current paradigm of halo cosmological distances.

In cosmological fireball models, a relativistically expanding fireball radiates at the shocks formed either as the ejecta within the fireball impact the surrounding medium (Rees & Meszaros 1992; Meszaros & Rees 1993; Meszaros, Rees, & Papathanssiou 1994; Katz 1994; Sari, Narayan, & Piran 1996) or as a consequence of inhomogeneities within the expanding fireball (Rees & Meszaros 1994; Paczynski & Xu 1994; Papathanssiou & Meszaros 1996). In these models, the spectrum extends from the gamma-ray to the optical band during the burst itself (see Papathanssiou & Meszaros 1996). In addition, the optical emission may last for hours after the end of the gamma-ray emission. The predicted optical flux and its temporal evolution are highly model-dependent. For example, in considering fading optical emission for a variety of models, Meszaros & Rees (1997) find \( 9 \leq m_V \leq 19 \), which fades as \( A \log t(s) \), where \( 3.75 \leq A \leq 15 \). These cosmological models will thus undoubtedly accommodate upper limits and possible detection from GROCSE and successor experiments.

The BATSE gamma-ray detectors provide burst positions localized only within wide angular limits, \( 1^\circ - 10^\circ \), depending on burst brightness and duration (Meegan et al. 1996). A system that seeks to detect an optical counterpart near simultaneously with the GRB must be on-location within a few seconds and image over a field of view roughly \( 15^\circ \) across. GROCSE was the first operational instrument satisfying these criteria. GROCSE systematically collected images of burst error boxes shortly after the bulk of the gamma-ray emission, and the GROCSE results place strong constraints on optical counterparts of fading GRB emission on time scales of tens of seconds from the GRB peak.

2. GROCSE INSTRUMENTATION

GROCSE received near–real-time GRB coordinates from BACODINE, which uses real-time data from the satellite, computes burst coordinates using the weighted triangulation method, and transmits the information via the Internet (Barthelmy et al. 1994). The “internal socket” protocol employed for data communication between NASA/Goddard Space Flight Center (GSFC) and our observation site at the Lawrence Livermore National Laboratory (LLNL) established special dedicated links to transmit and receive preformatted data packets. We verified the connection once per minute during observations by sending test packets. The link has transmitted data reliably for over 3 years. The average delay from the BATSE trigger to receipt by the GROCSE pointing and control software is \( \approx 5.5 \text{ s} \). Our electro-optical sensor and data recording equipment derived from a system originally constructed for a low Earth orbit satellite tracking program (Park 1990). It featured a very large, fast-slewing altitude-azimuth telescope mount and unique wide-field optics. The hardware is shown and illustrated schematically in Figure 1. A fish-eye lens constructed of solid blocks of concentric spherical elements produces uniform spot sizes across the entire lens field of view of \( 60^\circ \). The effective aperture of this lens is \( 89 \text{ mm} \), and the focal length is \( 250 \text{ mm} \). We covered the large spherical focal area (> 500 cm\(^2\)) with 23 segments of custom fiber optic reducers (3.8:1 reduction ratio). The front of each fiber bundle was machined to match the curvature of the spherical lens for best focus. Each focal reducer mapped an \( 8^\circ \times 11^\circ \) field of view onto an \( 8 \text{ mm} \times 13 \text{ mm} \) flat CCD area. The intensifiers had S-20 photocathodes sensitive to light in the wavelength range of 0.50–0.75 \( \text{µm} \). This photocathode response dominates the spectral sensitivity of the GROCSE system as the other optical components such as the lens and the CCDs have wider spectral range.

The schematic of the data acquisition system is shown in Figure 2. The 23 cameras were clocked synchronously by a master clock and timing distribution box. The gain of each intensifier was computer controlled through a Computer Aided Measurement and Control (CAMAC) interface. The exposure duration for all GROCSE images was set by the length of the intensifier gate pulse to 0.5 s. The entire lens and camera assembly was mounted on a Contraves, Goertz, Inc., computer-controlled inertial guidance indexing table. The mount provided a maximum angular slew rate of 100 \( \text{s}^{-1} \) with pointing precise to \( \approx 1^\circ \). Our data collection system was hosted by a Sun 4/330 computer. The camera output was directed to an 8 bit digitizer by means of a 23 channel video multiplexer. Following digitization, these data were collected and formatted by a Datacube image processing system, time-tagged using a WWVB clock, and then stored on disk. In addition, all GRB events were archived to Exabyte tape. The Sun 4/330 host also provided pointing commands to the Contraves, Goertz, Inc., mount via a General Purpose Interface Bus (GPIB) interface. In addition, the computer performed various housekeeping controls, such as monitoring the precipitation detector for indications of rain or fog and closing a weather tight clam shell over the instrument during periods of daylight or inclement weather. The online software automatically activated the instrument shortly after sunset and reestablished the connection to BACODINE. While awaiting GRB triggers, GROCSE collected data across the entire sky every 30 minutes, recording suitable sky background data for analysis of any GRB events across the entire unobstructed sky. We limited our observations to more than \( 30^\circ \) above the horizon because buildings surrounding the system, which was necessarily on site at LLNL, blocked the view at lower angles. This “sky patrol” was interrupted whenever BACODINE sent GRB coordinates. If such a coordinate set was within the field of regard of the telescope system and not within \( 30^\circ \) of the Moon, GROCSE was slewed at rapid rate to the location of the GRB candidate and images were recorded for 20 minutes after the trigger.

To protect the intensifiers from unexpected bright lights, the computer cycled through the cameras sequentially, raising each camera’s gain to its operating value long enough to take a picture, then lowering the gain back to zero and writing the image to disk. The exposure time for each image was \( 0.5 \text{ s} \), and the time between images was \( 5 \text{ s} \).
GROCSE then returned to "sky patrol" mode until either another GRB occurred or dawn broke. GROCSE's short exposure time made the probability of "accidentally" observing a GRB at burst onset nearly zero. The software was programmed to deactivate the camera and close the clam shell before dawn. GROCSE operated between 1994 January and 1996 June for 3800 hr (Lee et al. 1997). The instrument operated approximately 52% of available night hours. GROCSE recorded 22 burst triggers during the period of operation.

3. GROCSE GAMMA-RAY BURST OBSERVATIONS

The basic analysis strategy was to search the resulting images of GRB location for "new" starlike objects that do not appear in the star catalogues or in the background sky patrol images. The images were background-subtracted, flat-fielded, and subjected to a blob analysis that identified clusters of pixels whose intensities exceeded 5σ above the background fluctuations. Each image contained approximately 200 blobs. A human operator matched the image to a frame from the SAO and Guide Star catalog. In order to match the cataloged stars to our "blobs" unambiguously, first we convert the cataloged star locations into our pixel coordinates using a rotation matrix derived by matching well-recognized bright stars. Then we generate a simulated image using the stars within the camera's field of view. We used the stars with a magnitude brighter than 8.8. Then the operator carefully examined each blob from the GROCSE image and its relationship to the SAO star catalog image. Most of our search window (10 × 10 pixels) contained
single blobs unambiguously identified with known objects in the catalog. Many search windows were empty, as the 8.8 mag cutoff on objects from the catalog was fainter than GROCSE’s detection limits. In crowded star fields, some boxes contained multiple blobs. These cases were carefully examined and pattern matched to the stars in the catalog. There were also areas in the image especially toward the edges of the camera fields of view and also along areas of fiber bundle distortion where all blobs were systematically positioned outside of their respective search windows toward one particular direction. These cases were also examined carefully to assure that all the shifted blobs were associated with objects in the catalog. There were a few cases where adjacent hot pixels occasionally produced blobs above threshold that did not match the positions of any known objects in the catalog. Most of these were low Earth orbiting satellite tracks or bad pixels that were identified by examining background images taken with the same camera at different times. All images from 13 GRB triggers were examined in this fashion. None of the images contained any evidence for “new” starlike objects.

We derived upper limits to in-band fluxes of gamma-ray bursts shortly after outburst peaks by computing the sensitivity of GROCSE from observations of stars obtained in the GRB field. This process circumvented the need to radiometrically calibrate the individual sensors each night. Our data yield a completeness limit across observed gamma-ray burst events of $m_{\text{V,complete}} \sim 6.75 \pm 0.25$ 1 $\sigma$, which corresponds to a flux density of $F_{\lambda}(5500 \, \text{Å}) = 7.5 \pm 0.7 \times 10^{-23}$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$. Our limiting magnitude is $m_{\text{V,limit}} \sim 7.4 \pm 0.4$ 1 $\sigma$, or a respective flux density of $F_{\lambda}(5500 \, \text{Å}) = 4.1 \pm 0.8 \times 10^{-23}$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$. Note that the completeness magnitude is defined as the level for which all stars are observed, while the limiting magnitude is the brightness where only half the stars are observed.

The GROCSE GRB data are summarized in the first seven columns of Table 1. Column (1) lists the GRB name from their recorded UTC date. The BATSE trigger number is listed in column (2). We analyzed 13 of the 22 total GRBs. The other events were rejected because of cloud conditions or a large error in BACODINE position. Our measured limiting visual magnitude is shown in column (3), then converted to frequency-dependent flux at 5500 Å $F_{\lambda}(5500 \, \text{Å})$ as listed in column (4). Column (5) shows the time delay ($t_d$) from the beginning of the burst to the collection time of the optical images, and column (6) specifies the gamma-ray burst duration time ($T_{90}$) measured by BATSE. Columns (5) and (6) can be compared to see if a given GRB was imaged optically while the gamma-ray event was still in progress. Column (7) gives the percent of the BATSE 3 $\sigma$ error box imaged by GROCSE.

We have selected three BATSE triggers, GRB 951117, GRB 951124, and GRB 951220 from our observations to show some of the event characteristics and analysis. The Interplanetary Network (IPN; Hurley et al. 1994, 1997) annuli are available for these events, which give smaller positional error. Figures 3–5 shows BATSE light curves for the three events and the BATSE 3 $\sigma$ error circle for the three
... per square arcsecond. Unfortunately, the instrument was 10.2 per pixel for the best local limiting magnitude of 19.5...

\[ \frac{F_*}{V_T} \] 

Throughput differences between the cameras, due largely to varying sensitivities of the S-20 photocathodes, amount to \( \Delta m_{VT} \approx 0.2 \). This effect is significant but smaller than the star match magnitude error due to the predominance of the sky background.

We estimate our best-case scattered light level at about \( m_V = 8.0 \). Our resolution element angular size is 72 arcsec square, which corresponds to a background level of \( m_V = 10.2 \) per pixel for the best local limiting magnitude of 19.5 per square arcsecond. Unfortunately, the instrument was...
located near bright outdoor lighting, which increased the background by a factor of several due to scattering by local dust and aerosols. Events occurred at various angular distances from the Moon and at a variety of lunar phases, significantly increasing the background for certain events. The data show that both the limiting magnitude and the completeness of star matches varied between gamma-ray bursts by \( \Delta m_v \sim 0.5 \). Similar results are expected for sky background-limited data.

In summary, \( \Delta m_v \) complete \( \equiv m_v \) limit \( \equiv 0.5 \) over all events is consistent with the sky background variations dominating our flux uncertainty values, albeit with instrumental noise and a slight star temperature uncertainty contribution as well.

4. CONNECTION BETWEEN OPTICAL LIMITS AND GAMMA-RAY OBSERVATIONS: DISCUSSION AND SUMMARY

We want to relate the observed optical energy flux \( F_\nu (v_0) \), (units of ergs cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\)) at a fiducial frequency \( v_0 \) to the gamma-ray observations of the burst. For each burst, we have a series of optical upper limits from images taken between \( t_b \) and \( t_e \). Clearly an optical upper limit is more constraining for a bright GRB than for a weak one. The comparisons between the two energy bands are model-dependent since the choice of optical and gamma-ray quantities that are compared must be based explicitly or implicitly on an assumed physical connection between these quantities. In general, we have limits on the optical emission after the gamma-ray emission ends, while only in a few cases do we have limits on the optical emission during the burst. Nor can we say much about the bolometric optical emission because we do not know what spectral shape we are constraining. The comparisons between gamma-ray and optical quantities are not unique; in particular, they can be scaled by constant factors such as fiducial energies and frequencies. Ultimately, we present quantities that can be used to constrain detailed physical models. Our data support three different methods of comparing the optical and gamma-ray observations.

Suppose first that optical emission is produced in the same region as the gamma rays by related physical mechanisms. The optical flux then scales with the gamma-ray photon flux at a fiducial energy \( E_\gamma \), for example, if the optical spectrum is an extrapolation of the gamma-ray
spectrum (Ford & Band 1996). For an event captured optically while the GRB was still in progress, the optical $F_{\nu}(\nu_0)$ should be compared to the gamma-ray energy flux $F_c(E_c)$ (erg s$^{-1}$ cm$^{-2}$ keV$^{-1}$) at $E_c$ (keV) averaged over the same time period as the image corresponding to $F_\nu$. This comparison suggests a simple ratio

$$R_1 = 2.42 \times 10^{17} \frac{\text{Hz}}{\text{keV}} \frac{F_c}{F_c(E_c)}$$

(2)

or an effective energy spectral index

$$\alpha_{\nu_0} = \frac{\log \left[ (2.42 \times 10^{17} \text{ Hz keV}^{-1} \frac{F_c}{F_c(E_c)}) \right]}{\log \left( \frac{\nu_c}{\nu_0} \right)},$$

(3)

where $E_c$ and $\nu_0$ must be expressed in the same units.

In the second case, optical emission may result from immediate reprocessing of the gamma-ray flux. Then the optical flux at any moment during the burst would be proportional to the gamma-ray energy flux (ergs cm$^{-2}$ s$^{-1}$). If an optical image was accumulated from $t_b$ to $t_e = t_b + \Delta t$, $F_\nu$ should be compared with

$$\Phi_\gamma = \frac{1}{\Delta t} \int_{t_b}^{t_e} dt \int dE F_c(E, t),$$

(4)

where the integration proceeds over the model-dependent gamma-ray energy range. A useful dimensionless quantity is

$$R_2 = \frac{F_\nu \nu_0}{\Phi_\gamma}.$$  

(5)

In this expression, $\nu_0$ converts the optical energy flux per unit frequency into a broadband energy flux. This quantity is approximately the inverse of the Schaefer (1981) $L_c/L_{\text{opt}}$ integrated over the $B$ band.

Optical emission in a third case might be proportional to GRB fluence following a time delay. The most important strength measure would be the total GRB energy released, which is proportional to the burst fluence $\phi_\gamma$ observed at Earth. Thus the optical flux limits $F_\nu$ after the burst should be compared with $\phi_\gamma$. The ratio

$$R_3 = \frac{F_\nu}{\phi_\gamma}$$

(6)

is dimensionless (the units of $F_\nu$, ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$, include the dimensionless factor s$^{-1}$ Hz$^{-1}$). Note that optical $R_3$ could be multiplied by $\nu_0 \Delta t$ and still remain dimensionless. Multiplying $F_\nu$ by $\nu_0 \Delta t$ would convert the energy flux per unit frequency into a fluence; formally, this latter form of $R_3$ compares similar optical and gamma-ray
quantities. We are instead interested in describing the optical response at a given time to a burst of a specified intensity, so the characterization of the response a time after the burst should be independent of the time over which an image is integrated. We thus prefer to leave out this factor of $v_0 \Delta t$ from the definition of $R_3$.

GROCSE often did not view the error box until the burst was over. The comparison in such circumstances is best made between the optical upper limit and the gamma-ray fluence, or $R_3$ (eq. [6]). For those bursts where the optical observation occurred while the burst was still in progress, the gamma-ray fluence up to the time of the optical observation should be used, although in actuality both cases of a GROCSE observation occurring during a GRB caught only the trailing edge of the burst after almost all the GRB energy emission.

Adequate data are made available to accommodate calculation of such model-dependent temporal variations. Gamma-ray fluences can be derived from several types of BATSE data products. We have the highest confidence in fluences calculated by integrating the burst photon spectrum over energy and time when the spectrum is fit to the SHERB (Spectroscopic High Energy Resolution data from BATSE) data type, which provides sufficient spectral and temporal resolution. The SHERB data are a series of count spectra accumulated by the BATSE Spectroscopy Detectors (SDs); except for the longest bursts (none of which were observed by GROCSE), there are SHERB spectra after the end of each burst that help in extrapolating the background spectrum during the burst.

When there are no SHERB spectra for one reason or another (e.g., the SHERB spectra are not returned in the telemetry for weak bursts, or data are lost in telemetry gaps or gaps in collection), we used the fluences from the Third BATSE Gamma-Ray Burst Catalog et al. (Meegan 1996), when available. These fluences are provided over the 20–2000 keV range. Finally, we used fluences derived from fits to the Spacelab Tunnel Transfer Extension (STTE) spectra that are also from the SDs. The STTE data are the arrival times and energies of 64,000 counts around the time of the burst trigger from various detector modules; these counts can be accumulated over a variety of time scales. The STTE data do not necessarily span the entire burst duration, nor do they provide sufficient background data to assist in interpolating its background spectra at the time of the burst. Thus, we use the STTE data as a last resort.

The results of this comparison are presented in columns (8)–(10) of Table 1. Column (8) describes the gamma-ray fluence $\phi_2$ in units of ergs cm$^{-2}$ over the energy range 20–2000 keV. The ratio of optical flux to gamma-ray fluence
GROCSE optical flux limits from GRBs

TABLE 2
Calculation of Comparison Quantities for Selected Observations

| Name          | BATSE Trigger | $t_f$ (s) | $F_r(100$ keV)$^a$ | $\Phi_r$ | $R_1$ Upper Limit | $R_2$ Upper Limit |
|---------------|---------------|-----------|--------------------|----------|-------------------|-------------------|
| 940623 ...... | 3040          | 17.4      | $2.42 \times 10^{-10}$ | $9.28 \times 10^{-8}$ | $4.50 \times 10^{4}$ | $2.91 \times 10^{-1}$ |
| 951117 ...... | 3909          | 18        | $1.77 \times 10^{-10}$ | $6.26 \times 10^{-8}$ | $6.15 \times 10^{4}$ | $4.32 \times 10^{-1}$ |
| 951124 ...... | 3918          | 23.1      | $8.89 \times 10^{-10}$ | $5.94 \times 10^{-7}$ | $5.39 \times 10^{4}$ | $2.78 \times 10^{-1}$ |
| 951220 ...... | 4048          | 14.8      | $4.12 \times 10^{-10}$ | $2.66 \times 10^{-7}$ | $1.05 \times 10^{4}$ | $4.04 \times 10^{-2}$ |

* Time in seconds between burst trigger and GROCSE observation.
* Gamma-ray flux at 100 keV (ergs cm$^{-2}$ s$^{-1}$ keV$^{-1}$).
* Gamma-ray fluence (ergs cm$^{-2}$).

$R_3$, the ratio of the optical flux upper limit to the gamma-ray fluence, is shown in column (9). Note that this ratio is an upper limit. Column (10) provides notes as applicable to each burst. Table 2 shows values of $\Phi$, $R_1$, and $R_2$ for selected GRBs, as defined in equations (4), (2), and (5), respectively, for simultaneous optical gamma-ray emission. Note that the upper limits are given for the latter two quantities.

If the optical limit was set during the gamma-ray burst, upper limits for in-band gamma-ray flux can be computed based on extrapolating equation (2) to visible wavelengths. Burst spectra can be fitted with the “GRB” spectral function (Band et al. 1993). Here, the gamma-ray energy spectra are modeled in terms of two components: a high-energy component and a low-energy component of functional form

$$N(E) = \frac{F_r}{E_r} = AE^a e^{-E/E_0}, \quad E \leq (\alpha - \beta)E_0,$$  

(7a)

for low energies and

$$N(E) = BE^b, \quad E > (\alpha - \beta)E_0,$$  

(7b)

for high energies, where the parameters $A$, $\alpha$, $B$, and $\beta$ vary amongst gamma-ray bursts and $\alpha > \beta$. The energy break-point is chosen so that $N(E)$ and its derivative are continuous at $E_0$, typically 100 keV to greater than 1 MeV.

Fortuitously, several bursts appeared to be in progress at the moment of GROCSE imaging, among them GRB 951220 and GRB 951124. There are no SHERB data for GRB 951220, and the STTE data are inadequate to determine the gamma-ray flux during the optical observation. Thus, an energy flux from GRB 951220 may be computed from observations, although insufficient data exist to reconstruct a spectrum. The GRB 951124 optical observation occurred on the falling edge of the first of two gamma-ray flux peaks. Based on the evolution of the spectrum as gleaned from SHERB data, 90% of the energy flux resides in the first peak. Flux results up to the optical observation and for the entire event are presented in Table 1. The GROCSE observation began 30 s after the BACODINE trigger. The SHERB data were accumulated at the following posttrigger times: 26.75, 28.8, 31.30, and 34.30 s. Because of the small number of counts and variable count rate, as expected from a highly dynamic spectral evolution, determination of the instantaneous spectrum at $t = 30.0$ s is somewhat imprecise. The best fit is

$$N(E) = 8.413 \times 10^{-3} \left(\frac{E}{100 \text{ keV}}\right)^{-0.3464} e^{-E/85.9},$$

(8a)

$$E \leq 177.75 \text{ keV},$$

$$N(E) = 3.493 \times 10^{-3} \left(\frac{E}{100 \text{ keV}}\right)^{-2.416},$$

(8b)

$$E > 177.75 \text{ keV}.$$
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