**Observation of contemporaneous optical radiation from a γ-ray burst**


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The origin of γ-ray bursts (GRBs) has been enigmatic since their discovery. The situation improved dramatically in 1997, when the rapid availability of precise coordinates,3 for the bursts allowed the detection of faint optical and radio afterglows—optical spectra thus obtained have demonstrated conclusively that the bursts occur at cosmological distances. But, despite efforts by several groups4–7, optical detection has not hitherto been achieved during the first 25 seconds; the brightness then declines by a factor of 400. The situation improved dramatically in 1997, when the BATSE detector on board the Compton Gamma-Ray Observatory. Via rapid processing of the telemetry data stream, the GRB Coordinates Network 11 (GCN) can supply estimated coordinates to distant observatories within a few seconds. The apparatus is installed at Los Alamos National Laboratory in northern New Mexico.

Since March 1998, ROTSE-I has been active for ~75% of the total available nights, with most of the outage due to poor weather. During this period, ROTSE-I has responded to a total of 53 triggers. Of these, 26 are associated with GRBs and 13 are associated with soft γ-ray repeaters (SGRs). The median response time from the burst onset to start of the first exposure is 10 seconds.

During most of the night, ROTSE-I records a sequence of sky patrol images, mapping the entire visible sky with two pairs of exposures which reach a magnitude 5 sensitivity (mₜ) of 15. These data, approximately 8 gigabytes, are archived each night for later analysis. A GCN-provided trigger message interrupts any sequence in progress and initiates the slew to the estimated GRB location. A series of exposures with graduated times of 5, 75 and 200 seconds is then begun. Early in this sequence, the platform is ‘jogged’ by ±8° on each axis to obtain coverage of a four times larger field of view.

At 1999 January 23 09:46:56.12 UT, an energetic burst triggered the BATSE detector. This message reached Los Alamos 4 seconds later and the first exposure began 6 seconds after this. Unfortunately, a software error prevented the data from being written to disk. The first analyzable image was taken 22 seconds after the onset of the burst. The γ-ray light curve for GRB990123 was marked by an initial slow rise, so the BATSE trigger was based on relatively limited statistics. Thus the original GCN position estimate was displaced by 8.9° from subsequent localization, but the large ROTSE-I field of view was sufficient to contain the transient image. At 3.8 hours after the burst, the BeppoSAX satellite provided an X-ray localization12 in which an optical afterglow was discovered by Odewahn et al.13 at Mt Palomar. This BeppoSAX position enabled rapid examination of a small region of the large ROTSE-I field. A bright and rapidly varying transient was found in the ROTSE images at right ascension (RA) 15 h 25 min 30.2 s, declination (dec.) 44° 46° 0′, in excellent agreement with the afterglow found by Odewahn et al. (RA 15 h 25 min 30.53 s, dec. 44° 46° 0′.5°). Multiple absorption lines in the spectrum of the optical afterglow indicate a redshift of z > 1.6. Dark-subtracted and flattened ROTSE-I images of the GRB field are shown in Fig. 1. Details of the light curve are shown in Table 1.

By the time of the first exposure, the optical brightness of the transient had risen to mₜ = 11.7 mag. The flux rose by a factor of 13.7 in the following 25 seconds and then began a rapid, apparently smooth, decline. This decline began precipitously, with a power-law slope of ~2.5 and gradually slowed to give a slope of ~1.5. This decline, 10 minutes after the burst, agrees well with the power-law slope found hours later in early afterglow measurements14. These observations cover the transition from internal burst emission to external afterglow emission. The composite light curve is shown in Fig. 2.

**Table 1 ROTSE-I observations**

<table>
<thead>
<tr>
<th>Exposure start</th>
<th>Exposure duration</th>
<th>Magnitude</th>
<th>Camera</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 23 09:46:56.12 UT</td>
<td>75 s</td>
<td>14.8</td>
<td>C</td>
</tr>
<tr>
<td>22.18</td>
<td>75</td>
<td>11.70 ± 0.07</td>
<td>A</td>
</tr>
<tr>
<td>47.38</td>
<td>75</td>
<td>8.89 ± 0.02</td>
<td>A</td>
</tr>
<tr>
<td>72.67</td>
<td>75</td>
<td>9.97 ± 0.03</td>
<td>A</td>
</tr>
<tr>
<td>15712</td>
<td>75</td>
<td>11.86 ± 0.13</td>
<td>C</td>
</tr>
<tr>
<td>281.40</td>
<td>75</td>
<td>13.07 ± 0.04</td>
<td>A</td>
</tr>
<tr>
<td>446.67</td>
<td>75</td>
<td>13.91 ± 0.07</td>
<td>A</td>
</tr>
<tr>
<td>611.94</td>
<td>75</td>
<td>14.28 ± 0.12</td>
<td>A</td>
</tr>
<tr>
<td>2409.86</td>
<td>200</td>
<td>&lt;15.4</td>
<td>A</td>
</tr>
<tr>
<td>5333.98</td>
<td>800</td>
<td>&lt;16.1</td>
<td>A</td>
</tr>
</tbody>
</table>

Exposure start times are listed in seconds, relative to the nominal BATSE trigger time (1999 January 23 04:07:94 UT). Exposure durations are in seconds. Magnitudes are in the ‘V’ equivalent system described in Fig. 1 legend. Errors include both statistical errors and systematic errors arising from zero-point calibration. They do not include errors due to variations in the unknown spectral slope of the emission. Magnitude limits are 5e. The final limit results from co-adding the last four 200-s exposures and is quoted at the mean time of those exposures. Camera entries record the camera in which each observation was made.
Residuals for stars of magnitude 8.5±9.5 are
scheme. For each Tycho star, a "predicted ROTSE magnitude" is compared to the
standard, we estimate a "V equivalent" magnitude by the following calibration
to a wavelength range between 400 and 1,000 nm. Because this wide band is non-
with unfiltered CCDs. The optics and CCD quantum efficiency limit our sensitivity
from the images using SExtractor18. Astrometric and photometric calibrations are
averaging about 100 sky patrol (see text) images. Object catalogues are extracted
subtracting an average dark exposure. Flat field images are generated by median
arrow. South is up, east is left. Thermal effects are removed from the images by
optical transient (OT) is clearly detected in all images, and is indicated by the
top three images are 5-s exposures, the bottom three are 75-s exposures. The
are the CCD pixel coordinates. The sensitivity variations are due to exposure time;
recent previous sky patrol image was taken 130 minutes before the
positions argue strongly for a common origin. Third, the most
GRB flux and the spatial correlations to the X-ray and afterglow
peak. Second, the temporal correlation of the light curve with the
statistical significance of the transient image exceeds 160
Searches further back in time (55 images dating to 28 September
impossible to compensate for its presence. Magnitudes for the OT associated with
GRB990123, measured as described, are listed in Table 1. Further information
about the ROTSE-I observations is available at http://www.umich.edu/~rotse.

A number of arguments establish the association of our optical
transient with the burst and the afterglow seen later. First, the
statistical significance of the transient image exceeds 160σ at
the peak. Second, the temporal correlation of the light curve with the
GRB flux and the spatial correlations to the X-ray and afterglow
arguments strongly argue for a common origin. Third, the most
recent previous sky patrol image was taken 130 minutes before the
burst and no object is visible brighter than \( m_e = 14.8 \) mag. This is
the most stringent limit on an optical precursor obtained to date.
Searches further back in time (55 images dating to 28 September
also find no signal. Finally, the ‘axis jogging’ protocol places
the transient at different pixel locations within an image and even in
different cameras throughout the exposure series, eliminating the
possibility of a CCD defect or internal ‘ghost’ masquerading as a
signal.
The fluence of GRB990123 was exceptionally high (99.6 percentile of BATSE triggers; M. Briggs, personal communication), implying that such bright optical transients may be rare. Models of early optical emission suggest that optical intensity scales with γ-ray fluence\(^{15-17}\). If this is the case, ROTSE-I and similar instruments are sensitive to 50% of all GRBs. This translates to \( \sim 12 \) optically detected events per year. Our continuing analysis of less well-localized GRB data may therefore reveal similar transients. To
date, this process has been hampered by the necessity of identifying and discarding typically 100,000 objects within the large field of view and optimizing a search strategy in the face of an unknown
early time structure. The results we report here at least partially
resolve the latter problem while increasing the incentive to complete
a difficult analysis task. The ROTSE project is in the process of
completing two 0.45-m telescopes capable of reaching 4 magnitudes
deepen than ROTSE-I for the same duration exposures. If γ-ray
emission in bursts is beamed but the optical emission is more
isotropic, there may be many optical transients unassociated with
detectable GRBs. These instruments will conduct sensitive searches

Figure 1 Time series images of the optical burst. Each image is 24° on a side, and
represents \( 6 \times 10^{-3} \) of the ROTSE-I field of view. The horizontal and vertical axes
are the CCD pixel coordinates. The sensitivity variations are due to exposure time;
the top three images are 5-s exposures, the bottom three are 75-s exposures. The
optical transient (OT) is clearly detected in all images, and is indicated by the
arrow. South is up, east is left. Thermal effects are removed from the images by
subtracting an average dark exposure. Flat field images are generated by median
averaging about 100 sky patrol (see text) images. Object catalogues are extracted
from the images using SExtractor\(^{18}\). Astrometric and photometric calibrations are
determined by comparison with the ~1,000 Tycho\(^{19}\) stars available in each image.
Residuals for stars of magnitude 8.5–9.5 are \(< 1.2\). These images are obtained
with unfiltered CCDs. The optics and CCD quantum efficiency limit our sensitivity
to a wavelength range between 400 and 1,000 nm. Because this wide band is non-
standard, we estimate a "V equivalent" magnitude by the following calibration
scheme. For each Tycho star, a "predicted ROTSE magnitude" is compared to the
2.5 pixel aperture fluxes measured for these objects to obtain a global zero point
for each ROTSE-I image. For the Tycho stars, the agreement between our
predicted magnitude and the measured magnitude is ±0.15. These errors are
dominated by colour variation. The zero points are determined to ±0.02. With
large pixels, we must understand the effects of crowding. (This is especially true as we follow the transient to ever fainter magnitudes.) To check the effect of such
crowding, we have compared the burst location to the locations of known objects
from the USNO A2.0 catalogue\(^{20}\). The nearest object, 34" away, is a star with
R-band magnitude \( R = 19.2 \). More important is an \( R = 14.4 \) star, 42" away. This
object affects the measured magnitude of the OT only in our final detection. It can
be seen in the final image to the lower right of the OT. A correction of ±0.15 is
applied to compensate for its presence. Magnitudes for the OT associated with
GRB990123, measured as described, are listed in Table 1. Further information
about the ROTSE-I observations is available at http://www.umich.edu/~rotse.
Figure 2. A combined optical light curve. Afterglow data points are drawn from the GCN archive\textsuperscript{21–23}. The early decay of the ROTSE-I light curve is not well fitted by a single power law. The final ROTSE limit is obtained by co-adding the final four 200-s images. The inset shows the first three ROTSE optical fluxes compared to the BATSE-\gamma-ray light curve in the 100–300 keV energy band. The ROTSE-I fluxes are in arbitrary units. Horizontal error bars indicate periods of active observation. We note that there is no information about the optical light curve outside these intervals. Vertical error bars represent flux uncertainties. Further information about GCN is available at \url{http://gcn.gsfc.nasa.gov/gcn}.}

for such events. We expect that ROTSE will be important in the exploration to come.

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11. Barthelmy, S. et al. in Gamma-Ray Burst: 4th Huntsville Symp. Ultrasonically driven gas bubbles in liquids can emit intense bursts of light when they collapse\textsuperscript{2}. The physical mechanism for single-bubble sonoluminescence has been much debated\textsuperscript{2,3}. The conditions required for, and generated by, bubble collapse can be deduced within the framework of a hydrodynamic (Rayleigh–Plesset\textsuperscript{4}) analysis of bubble dynamics and stability\textsuperscript{5,6}, and by considering the dissociation and outward diffusion of gases under the extreme conditions induced by collapse\textsuperscript{7,8}. We show here that by extending this hydrodynamic/chemical picture in a simple way, the light emission can be explained too. The additional elements that we add are a model for the volume dependence of the bubble’s temperature\textsuperscript{8,10}, and allowance for the small emissivity of a weakly ionized gas\textsuperscript{11}. Despite its simplicity, our approach can account quantitatively for the observed parameter dependences of

**A simple explanation of light emission in sonoluminescence**

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