The Robotic Optical Transient Search Experiment (ROTSE) seeks to measure simultaneous and early afterglow optical emission from gamma-ray bursts (GRBs). A search for optical counterparts to six GRBs with localization errors of 1 deg² or better produced no detections. The earliest limiting sensitivity is m_{ROTSE} > 13.1 at 10.85 s (5 s exposure) after the gamma-ray rise, and the best limit is m_{ROTSE} > 16.0 at 62 minutes (897 s exposure). These are the most stringent limits obtained for the GRB optical counterpart brightness in the first hour after the burst. Consideration of the gamma-ray fluence and peak flux for these bursts and for GRB 990123 indicates that there is not a strong positive correlation between optical flux and gamma-ray emission.

Subject headings: gamma rays: bursts — gamma rays: observations
ROTSE-I first triggered on GRB 980329 and began the first exposures 11.5 s after the burst had started. Unfortunately, the sky was cloudy for the early data and hazy for the later images. Nevertheless, some early images are clear enough in the immediate region of the burst for us to detect 10th magnitude objects. To maximize sensitivity in later, clearer images, we co-added two and three frames, respectively, in order to get the last two observations. GRB 980401 occurred during focusing tests, so a manual response of eight exposures was performed. The last four 125 s exposures were co-added into one observation spread over 897 s. The final localization for GRB 980420 places it near the Galactic plane (most probably \( g_b \approx -10^9 \)), and the focused images are very crowded. The optics of the two cameras covering the main part of the IPN arc, however, were poorly focused. The final localization for GRB 980627 places a majority of the probable area outside of even tiled exposures, with the result that we have 40% coverage in only four tiled images. The observing conditions for GRB 981121 and GRB 981223 were good.

We dark-subtracted and flat-fielded the raw images, and we followed that up by source-finding the corrected images using SExtractor (Bertin & Arnouts 1996). We then performed astrometric and photometric calibrations by comparing the images with those in the Hipparcos catalog (Hög et al. 1998). Our astrometric errors are 1.43. Since we operate with unfiltered CCDs to maximize our light-gathering ability, photometry is established by comparing raw ROTSE magnitudes with \( V \)-band measures and color correcting based on \( B-V \). The resulting magnitude, \( m_{\text{ROTSE}} \), corresponds on average to \( m_V \) but includes sensitivity in the \( B, V, I \), and especially \( R \) bands. Our photometric errors are 0.02 mag for stars brighter than 12th magnitude.

3. ANALYSIS AND DISCUSSION

Due to the observation of an X-ray counterpart to GRB 980329, optical (Djorgovski et al. 1998; Palazzi et al. 1998; Pedersen et al. 1998) and radio (Taylor et al. 1998) counterparts were observed several hours later. For such precise localizations, we would accept any detection at the known location of the burst. No optical emission was observed, and so for the early images, we take the sensitivity to be 0.5 mag brighter than the dimmest SAO and GSC stars visible in the immediate region of the burst. We calculated the limiting sensitivities for the co-added frames by extrapolating the Hipparcos-derived calibration to our 5 \( \sigma \) threshold. A cross-check of this calibration was performed by directly comparing it with the USNO catalog and finding the faintest \( m_{\text{ROTSE}} \) to which we are more than 50% efficient. Given the afterglow measurements, we are able to place a constraint on the overall power-law decline of optical emission from GRB 980329 that is shallower than \( t^{-1.8} \) with respect to the earliest afterglow detection. This contrasts with the faster decline of the X-ray emission (Greiner et al. 1998).

For the other bursts, we require that a source magnitude vary by at least 0.5 + \( \sigma \), where \( \sigma \) is the statistical error on the dimmest measurement. Varying objects are only considered bona fide optical counterpart candidates if they appear in at least two successive images. This removes backgrounds such as cosmic rays and satellite glints that show up frequently in ROTSE-I images. No rapidly varying objects were found in the allowed error regions of these five bursts. The image sensitivities were determined from the Hipparcos calibration as described above, and in most cases they were cross-checked with the USNO catalog for comparison.

Limiting magnitudes are given in Table 2 for up to three

### Table 1

**Characteristics of Six Bursts Responded to by ROTSE-I**

| GRB    | BATSE Trigger Number | \( T_{90} \) (s) | \( \phi_{\text{max}} \) (photons cm\(^{-2}\) s\(^{-1}\)) | Source | Coverage (%) | \( t_f \) (s) |
|--------|----------------------|------------------|---------------------------------|--------|--------------|-------------|
| 980329 | 6665                 | 19               | 322                             | 13.8   | SAX          | 100 (100)   | 11.5       |
| 980401 | 6672                 | 28               | 40                              | 5.60   | IPN          | 87          | 2478       |
| 980420 | 6694                 | 40               | 77                              | 4.28   | IPN          | 90 (96)     | 28.99      |
| 980627 | 6880                 | 11               | 7                               | 1.27   | IPN          | ... (40)    | 11.97      |
| 981121 | 7219                 | 54               | 70                              | 1.33   | IPN          | 100 (100)   | 14.51      |
| 981223 | 7277                 | 30               | 128                             | 7.44   | IPN          | 100 (67)    | 8.35       |
| 990123 | 7343                 | 63               | 1020                            | 17.0   | SAX          | 100 (100)   | 22.18      |

* For comparison, corresponding information for GRB 990123 is also given (Akerlof et al. 1999).
* \( t_{90} \) is the duration of the burst.
* \( \phi_{\text{max}} \) is the peak flux.
* Coverage of the GRB probability. Coverages for tiled epochs are indicated in parentheses.
* \( t_f \) is the time for first image recorded.

### Table 2

**Summary of Limits for Six Bursts Responded to by ROTSE-I**

| GRB    | \( t_i \) (s) | \( \Delta t_i \) (s) | \( m_{\text{ROTSE}(t_i)} \) | \( t_2 \) (s) | \( \Delta t_2 \) (s) | \( m_{\text{ROTSE}(t_2)} \) | \( t_f \) (s) | \( \Delta t_f \) (s) | \( m_{\text{ROTSE}(t_f)} \) |
|--------|--------------|---------------------|----------------------------|--------------|---------------------|----------------------------|--------------|---------------------|----------------------------|
| 980329 | 51.5         | 5                   | 9.5                        | 416          | 25                  | 10.5                       | 2239         | 390                 | 14.7                       |
| 980401 | ...          | ...                 | ...                        | 2485         | 15                  | 14.1                       | 3726         | 897                 | 16.0                       |
| 980420 | 31.49        | 5                   | 11.1                       | 176.32       | 5                   | 12.4                       | 578.21       | 25                  | 12.5                       |
| 980627 | ...          | ...                 | ...                        | 180.49       | 5                   | 13.2                       | 601.87       | 25                  | 13.6                       |
| 981121 | 17.01        | 5                   | 13.3                       | 219.28       | 25                  | 14.9                       | 742.05       | 125                 | 15.3                       |
| 981223 | 10.85        | 5                   | 13.1                       | 90.13        | 5                   | 14.7                       | 736.43       | 75                  | 15.3                       |

* The columns list up to three epochs (middle of exposure, in seconds) and their exposure length (in seconds) and sensitivity.
epochs, marking significant improvements in sensitivity. Figure 1 displays all relevant observations for which the coverage exceeded 50% and illustrates that ROTSE-I has a sensitivity to optical bursts significantly fainter than GRB 990123. The earliest limit is \( m_{\text{ROTSE}} > 13.1 \) at 10.85 s for GRB 981223. The best limit of this sample is \( m_{\text{ROTSE}} > 16.0 \) at 62 minutes for GRB 980401. We can conclude that bright optical counterparts (i.e., \( m > 10 \)) are uncommon.

Since prompt optical emission has been seen in GRB 990123, we ask whether optical emission from a GRB is correlated with gamma-ray output, as is suggested by Sari & Piran (1999). Because we do not know whether fluence or peak flux are accurate measures of the total gamma-ray emission, we consider both in our comparison. To bring all bursts toward a common footing, we first adjust their \( m_{\text{ROTSE}} \) limits by 2.5 log \( \frac{\text{fluence}}{\text{fluence}_{\text{GRB 990123}}} \), where \( f \) is the gamma-ray fluence. We calculate this fluence to be that measured in the BATSE 50–100 keV plus 100–300 keV channels to avoid systematics that are due to problems in the spectral fitting of the other channels (M. Briggs 1999, private communication). These fluence-scaled limits are plotted, along with the GRB 990123 observations, in Figure 2. We have also adjusted our optical limits by scaling according to the BATSE measure of peak flux in the 64 ms binning of the 50–300 keV data (see Fig. 3).

The variation of Galactic extinction over the IPN arcs prevents us from quoting an accurate value for most of these bursts. However, it is much less than 1 mag at their most probable locations. Since GRB 990123 has a similar low value of extinction (=0.04), the effect of Galactic extinction on our comparison should be minimal. The one exception is GRB 980420, which may have over 2 mag of extinction. Although extinction near the source can only be measured for GRB 980329, it is likely that most GRBs are not so heavily obscured since the great majority that are observed to have both X-ray and radio counterparts also exhibit optical emission (Frail et al. 2000).

Under the assumption of gamma-ray scaling, ROTSE-I is sensitive to GRB 990123–like optical bursts for GRB 981223 from 30 to 300 s. At around 1 minute, the optical emission of GRB 981121 and of GRB 981223 would have been more than 2 mag over our detection threshold. Either GRB 990123 is atypical of GRBs in general or there is not a strong correlation of optical flux with gamma-ray emission, and the inherent dispersion to any actual correlation must be larger than 2 mag in order to explain the results from GRB 981121 and GRB 981223.

4. CONCLUSIONS

In a study of six well-localized gamma-ray bursts, no optical counterparts were identified. When compared with afterglow observations of GRB 980329, we constrain the overall power-law decay of the optical emission to be shallower than \( t^{-1.8} \). When using either gamma-ray fluence or peak flux as a predictor of optical emission, we find that especially at around 1 minute, optical emission is at least 2 mag dimmer than for GRB 990123. This nondetection of another optical burst indicates that optical emission is not strongly correlated with gamma-ray output.

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