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# LOTIS, SUPER-LOTIS, SDSS AND TAUTENBURG OBSERVATIONS OF GRB 010921

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## ABSTRACT

We present multi-instrument optical observations of the High Energy Transient Explorer (HETE-2)/Interplanetary Network (IPN) error box of GRB 010921. This event was the first gamma ray burst (GRB) localized by HETE-2 which has resulted in the detection of an optical afterglow. In this paper we report the earliest known observations of the GRB010921 field, taken with the 0.11-m Livermore Optical Transient Imaging System (LOTIS) telescope, and the earliest known detection of the GRB010921 optical afterglow, using the 0.5-m Sloan Digital Sky Survey Photometric Telescope (SDSS PT). Observations with the LOTIS telescope began during a routine sky patrol 52 minutes after the burst. Observations were made with the SDSS PT, the 0.6-m Super-LOTIS telescope, and the 1.34-m Tautenburg Schmidt telescope at 21.3, 21.8, and 37.5 hours after the GRB, respectively. In addition, the host galaxy was observed with the USNOFS 1.0-m telescope 56 days after the burst. We find that at later times (t > 1 day after the burst), the optical afterglow exhibited a power-law decline with a slope of $\alpha = 1.75 \pm 0.28$. However, our earliest observations show that this power-law decline can not have extended to early times (t < 0.035 day).

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

## 1. INTRODUCTION

The High Energy Transient Explorer (space.mit.edu/HETE/) HETE-2 is dedicated to the study of gamma-ray bursts (GRBs). HETE-2 is currently the only GRB detector capable of localizing and disseminating GRB coordinates in near real-time. Low-energy emission during and shortly after a GRB ($t \lesssim 1$ hr) potentially holds the key to significant progress in understanding the central engine of GRBs and could provide valuable clues to their progenitors (Mészáros 2001).

The HETE-2 detection of GRB 010921 together with data from the Interplanetary Network (IPN) provided the first HETE-2 localization which has resulted in the detection of an optical afterglow. Although the afterglow was relatively bright, early observations of the error box failed to reveal any candidate afterglows because of source confusion with its bright host galaxy ($R \sim 21.7$) (Price et al. 2001). Spectroscopy of the host galaxy performed with the Palomar 200-in telescope four weeks after the burst indicates a redshift of $z = 0.450 \pm 0.005$ (Djorgovski et al. 2001).

## 2. OBSERVATIONS

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### 2.1. *GRB Observations by HETE-2 and IPN*

On 21 September 2001 at 05:15:50.56 UT (September 21.21934 UT) the Fregate instrument detected a bright GRB (Trigger 1761). GRB 010921 had a duration of $\sim 12$ s in the 8-85 keV band, a peak flux of $F_p > 3 \times 10^{-7}$erg cm$^{-2}$ s$^{-1}$ and a fluence of $S \sim 1 \times 10^{-6}$erg cm$^{-2}$ (Ricker et al. 2001). For a spatially flat FRW cosmology ($\Omega_m$ = 0.3 , $\Omega_\Lambda$ = 0.7, and $H_0$ = 65 km s$^{-1}$ Mpc$^{-1}$) the measured redshift implies an equivalent isotropic energy release of $6 \times 10^{50}$ erg. This inferred energy would be within the range suggested by Frail et al. (2001) for the standard energy reservoir, $E_0 \sim 5 \times 10^{50}$ erg, suggesting the opening angle of the gamma-ray jet in GRB 010921 is modest.

The burst was also detected in the Wide Field X-ray Monitor WXM X detector but was outside the field-of-view of the WXM Y detector (Ricker et al. 2001b). Because the GRB was not well localized in the Y direction, a location was not distributed with the real-time trigger. Approximately five hours after the GRB, ground analysis gave a long narrow error box ($\sim 10° \times \sim 20'$) centered at $\alpha, \delta$ = $23^h2^m14^s\!.6, 44°16'4.8''$ (J2000.0) (Ricker et al. 2001). *Ulysses* and *BeppoSAX* also detected GRB010921. These detections resulted in an IPN triangulation approximately 15 hours after the burst. The IPN location for the burst is an annulus centered at $\alpha, \delta$ = $15^h29^m11^s\!.8, 67°36'18.0''$ (J2000.0), with radius of $60°\!.003 \pm 0°\!.156 (3\sigma)$. The combined HETE-2/IPN data resulted in an error box with an area of a 310$\square'$ box with corners at $\alpha_1, \delta_1$ = $22^h54^m21^s\!.87, 40°36'25.84''$, $\alpha_2, \delta_2$ = $22^h54^m52^s\!.09, 40°54'33.20''$, $\alpha_3, \delta_3$ = $22^h56^m7^s\!.16, 40°45'22.04''$, $\alpha_4, \delta_4$ = $22^h56^m37^s\!.60, 41°3'29.06''$, (J2000.0) (Ricker et al. 2001b).

### 2.2. *LOTIS Observations*

Although no coordinates were distributed with the real-time HETE-2 trigger, the $f/1.8$, 0.11-m LOTIS telescope (Park et al. 1998) observed the position of the error box during routine sky patrol on September 21 UT at 21.255 UT and 21.417 UT, only 52 min and 4.75 hours after the GRB. The LOTIS telescope consists of four lens/camera systems directed toward a common $8°\!.8 \times 8°\!.8$ field-of-view. Two of the LOTIS cameras are equipped with clear filters, one with a standard Cousins $R$ filter, and one with the standard Johnson $V$ filter. During sky patrol observations the LOTIS telescope obtained 50 s exposures at each position on the sky.

### 2.3. *SDSS PT Observations*

GRB010921 was also observed with the Sloan Digital Sky Survey's (SDSS; York et al. 2000) Photometric Telescope (PT), which is located at Apache Point Observatory (APO) in Sunspot, New Mexico. The PT is an $f/8.8$, 0.5-m telescope equipped with $u'g'r'i'z'$ filters. The SDSS is designed to be on the $u'g'r'i'z'$ photometric system described in Fukugita et al. (1996) which is an $AB_\nu$ system where flat spectrum objects ($F_\nu \propto \nu^0$) have zero colors. However, the current photometric calibration of the PT may differ from this system by at most a few percent (Stoughton et al. 2002), and we therefore denote the PT photometric magnitudes by $u*g*r*i*z*$. The single SITe $2048 \times 2048$ CCD camera has a $41.5' \times 41.5'$ field-of-view. On September 22 UT beginning at 22.108 UT (21.33 hours after the GRB) 200 s exposures were taken in each of the $u'g'r'i'z'$ filters, and on September 23 UT, beginning at 23.224 UT 200 s and 400 s exposures were taken in each of the same filters (Lamb et al. 2001). Observations on both nights covered the entire improved HETE-2 error box (Ricker et al. 2001, Hurley et al. 2001). Since the GRB exposures were unusually long, the afterglow was near the sky level in most of the images, and conditions were cloudy at the time, magnitude errors are uncharacteristically large.

### 2.4. *Super-LOTIS Observations*

The center of the IPN error box for GRB 010921 was added to the Super-LOTIS sky patrol table and observations of the location began shortly after nightfall on September 22.128 UT. Super-LOTIS is an $f/3.5$, 0.6-m Boller&Chivens telescope at Kitt Peak near Tucson, Arizona. Its focal plane array is a Loral $2048 \times 2048$ CCD camera covering $51' \times 51'$ field-of-view. The telescope system is fully automated and is capable of responding to a real-time GRB trigger within 30 seconds. A total of twenty 50-second exposures were obtained during the first epoch. Super-LOTIS re-observed the field on September 22 and 23 UT beginning at 22.267, 23.128, and 23.269 UT. Each of these observations also consisted of twenty 50-second exposures. For these observations, no astronomical filter was used.

### 2.5. *Tautenburg Observations*

On September 22.781 the Tautenburg Schmidt telescope began observations of the error box in the Johnson $I$-band. This telescope, located at Tautenburg, Germany, is an f/2, 1.34-m aperture telescope equipped with a SITe $2048 \times 2048$ CCD as the focal plane array. Its field-of-view is $36' \times 36'$. Thirty-eight 120-second exposures were acquired. The same field was re-observed on October 25 and eight 120-second exposures were acquired. During these exposures, the telescope was dithered to allow a better treatment of bad pixels.

### 2.6. *USNOFS Host Galaxy Observations*

On November 17 UT (56 days after the burst), the USNOFS 1.0-m telescope at Flagstaff, Arizona, observed the GRB010921 area to determine the brightness of the host galaxy in $Rc$ and $Ic$-bands. The USNOFS is an f/7.3 telescope equipped with $UBVRI$ filters; its focal plane arrays are a SITe/Tektronix $2048 \times 2048$ CCD with $23' \times 23'$ field-of-view. For these observations, eight 600-second exposures per filter were acquired and coadded.

## 3. RESULTS

Early observations of the error box of GRB 010921 with large aperture telescopes found no evidence of an optical afterglow to the limit of the DPOSS plates, $R \sim 20.5$ (Fox et al. 2001; Henden et al. 2001b). However, follow-up observations by Price et al. (2001) resulted in the report of a fading source which displayed the characteristic decay behavior of a GRB afterglow. The coordinates of the suspected afterglow are $\alpha, \delta$ = $22^h55^m59.92^s\!.9, +40°55'52.83''$ (J2000.0).

Following the reported detection of an optical afterglow candidate, we searched our images for the optical afterglow. In the LOTIS clear- and $V$-band images taken 52 min after the burst we found no optical transient (OT) brighter than $m_{clear} > 15.2 \pm 0.15$ and $V > 15.6 \pm 0.15$. The shutter for the $R$-band camera failed to open. In the second epoch of LOTIS clear- and $V$-band images taken at September 21.417 UT (4.75 hours after the burst) we found no OT to the same limiting magnitude.

Analysis of the SDSS PT images obtained on September 22 UT reveals the optical afterglow at $g* = 20.8 \pm 0.6, r* =$

$19.5 \pm 0.3$, and $i* = 18.8 \pm 0.7$, and gives $3\sigma$ upper limits of $u* > 20.5$ and $z* > 15.0$. Analysis of the SDSS PT images obtained on September 23 UT reveals the optical afterglow at $g* = 22.4 \pm 1.0$ and $r* = 21.5 \pm 1.0$, and gives $3\sigma$ upper limits of $u* > 19.5$, $i* > 18.5$, and $z* > 18.0$. The completeness upper limits are the magnitudes at which the probability of detection is 100%. Because of variable extinction over the field due to clouds, the 50% detection limits are more than a magnitude fainter than the completeness limits. The top panel of Figure 1 (*a* to *e*) shows the SDSS PT images in $u'g'r'i'z'$ obtained on September 22 UT of the GRB010921 afterglow area (marked by a circle) reported by Price et al. (2001).

We searched for the OT in the Super-LOTIS data by co-adding twenty images obtained during each epoch, two epochs per night. In the first co-added image, which was taken on September 22 UT beginning at 22.128 UT, we detect the optical afterglow at $m_{\rm clear} = 19.4 \pm 0.2$ at 15 $\sigma$ above noise level. The same analysis applied to the second epoch data (September 22.267 UT) detects the optical afterglow at $m_{\rm clear} = 19.9 \pm 0.2$ at 12 $\sigma$ above the noise level. Panels *f* and *g* of Figure 1 show the co-added images with the afterglow indicated by an arrow. We also searched for an OT in the data set obtained on September 23 UT and find no afterglow to the 10 $\sigma$ noise limit of $m_{\rm clear} = 21.1 \pm 0.3$.

The Tautenburg data taken on September 22 UT and October 25 UT were co-added to search for the GRB 010921 afterglow. Panel *h* of Figure 1 show the location of the afterglow indicated by an arrow. Calibrating the afterglow against secondary standards (Henden et al. 2001a), the brightness of the afterglow is estimated as $I = 19.32 \pm 0.08$. The host galaxy is marginally detected at the 5 $\sigma$ level in the second epoch image (October 25 UT at 25.770) at $I = 20.94 \pm 0.26$ (Panel *i* of Figure 1).

The USNOFS deep imaging data was analyzed to obtain the brightness of the host galaxy. The host galaxy was clearly visible in the coadded image 56 days after the burst and we determine its brightness to be $Rc = 21.93 \pm 0.09$ and $Ic = 21.05 \pm 0.08$.

## 4. IMPLICATIONS AND CONCLUSIONS

Table 1 summarizes the magnitudes and upper limits in the various filters from all the above observations. We transformed the fluxes measured in various filters to the *R* filter by normalizing a $\beta = -2.3$ power-law spectrum (Price et al. 2001; Kulkarni et al. 2001) to the effective wavelength and flux of each data point, and then plotting the point at the effective wavelength of the *R*-band. This calculated values are listed in the last column of Table 1. Figure 2 shows the resulting light curve of the optical afterglow of GRB 010921. We fit the data with a power law decay plus a constant host galaxy flux, $F = F_0(t-t_0)^{-\alpha} + F_{host}$. We obtain a best fit decay index of $\alpha = 1.75 \pm 0.28$ applying a host galaxy magnitude of $R = 21.93$ from the USNO measurements performed 56 days after the burst. This is a typical value for an optical afterglow prior to the jet break, which is predicted to take place $\sim 130$ days after the GRB based on the observed energetics of this burst (Djorgovski et al. 2001). The optical afterglow reported by Price et al. (2001) was $R = 19.6 \pm 0.3$ on September 22 and significantly fain.ter on September 23 (we place a limit on *R* of roughly 20.5).

We attempt to constrain the early-time power law decay by extrapolating the best-fit power-law decay model back to the LOTIS upper limit of $R > 15.0$ on September 21.256. Figure 2 shows that the early-time LOTIS upper limits are inconsistent with an unchanging decay index from $t - t_0 = 52$ min to $t - t_0 > 20$ h. This may suggest that the optical emission peaked at a magnitude fainter than the LOTIS limiting magnitude, (perhaps similar to the afterglow of GRB 970508) or that the slope changed between the observations, as suggested in the case of GRB 991208 (Castro-Tirado et al. 2001). Complex light curve shapes at very early times have been observed (e.g., GRB970805) and can be explained in terms of a distribution of Lorentz factors produced by the central engine (Rees and Meszaros 1998) and the complex evolution of multi-component shock emission in a relativistic fireball (Kobayashi 2000).

Our early time observations show that afterglow behavior can change quickly within hours after the burst. With rapid localizations we can probe the transition from the prompt emission phase to the subsequent unfolding of the canonical afterglow phase. GRB010921 only provided an upper limit 52 minutes after outburst, but HETE-2 triggers should eventually allow us to obtain simultaneous flux measurements. Robotic telescopes like LOTIS and Super-LOTIS are well suited to finding this early-time emission in response to a near real-time localization of the GRB by HETE-2.

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TABLE 1
OBSERVATIONS OF GRB 010921.

| Date UT | $\Delta$T (days) | Telescope | Filter | Exposure Time (s) | Magnitude | *R*equivalent Magnitude |
|---|---|---|---|---|---|---|
| Sep 21.219 | 0.000 | HETE-2 | GRB010921 | | | |
| Sep 21.255 | 0.036 | LOTIS | Clear | $1 \times 50$ s | $> 15.2 \pm 0.15$ | $> 15.04$ |
| Sep 21.255 | 0.036 | LOTIS | *V* | $1 \times 50$ s | $> 15.6 \pm 0.15$ | $> 15.05$ |
| Sep 21.417 | 0.198 | LOTIS | Clear | $1 \times 50$ s | $> 15.2 \pm 0.15$ | $> 15.04$ |
| Sep 21.255 | 0.198 | LOTIS | *V* | $1 \times 50$ s | $> 15.6 \pm 0.15$ | $> 15.05$ |
| Sep 22.108 | 0.889 | SDSS PT | $u*$ | 500 s | $> 20.5 \pm 0.5$ | $> 19.82$ |
| Sep 22.112 | 0.893 | SDSS PT | $g*$ | 200 s | $20.8 \pm 0.6$ | 19.85 |
| Sep 22.115 | 0.896 | SDSS PT | $r*$ | 200 s | $19.5 \pm 0.3$ | 19.44 |
| Sep 22.118 | 0.899 | SDSS PT | $i*$ | 200 s | $18.8 \pm 0.7$ | 19.49 |
| Sep 22.121 | 0.902 | SDSS PT | $z*$ | 200 s | $> 15.0 \pm 0.5$ | $> 15.39$ |
| Sep 22.128 | 0.909 | Super-LOTIS | Clear | $20 \times 50$ s | $19.4 \pm 0.1$ | 19.24 |
| Sep 22.267 | 1.048 | Super-LOTIS | Clear | $20 \times 50$ s | $19.9 \pm 0.1$ | 19.54 |
| Sep 22.781 | 1.562 | Tautenburg | *Ic* | $38 \times 120$ s | $19.32 \pm 0.08$ | 20.05 |
| Sep 23.128 | 1.909 | Super-LOTIS | Clear | $20 \times 50$ s | $> 21.1 \pm 0.3$ | $> 20.94$ |
| Sep 23.244 | 2.025 | SDSS PT | $u*$ | 500 s | $> 19.5 \pm 0.5$ | $> 18.82$ |
| Sep 23.249 | 2.030 | SDSS PT | $g*$ | 400 s | $22.4 \pm 1.0$ | 21.45 |
| Sep 23.255 | 2.036 | SDSS PT | $r*$ | 400 s | $21.5 \pm 1.0$ | 21.44 |
| Sep 23.260 | 2.041 | SDSS PT | $i*$ | 400 s | $> 18.5 \pm 0.5$ | $> 19.19$ |
| Sep 23.266 | 2.047 | SDSS PT | $z*$ | 400 s | $> 18.0 \pm 0.5$ | $> 19.18$ |
| Sep 23.269 | 2.050 | Super-LOTIS | Clear | $20 \times 50$ s | $> 21.2 \pm 0.3$ | $> 20.94$ |
| Oct 25.770 | 34.551 | Tautenburg | *Ic* | $8 \times 120$ s | $20.94 \pm 0.26$ | 21.67 |
| Nov 17.7 | 56.700 | USNOFS | *Rc* | $8 \times 600$ s | $21.93 \pm 0.09$ | 21.93 |
| Nov 17.7 | 56.700 | USNOFS | *Ic* | $8 \times 600$ s | $21.05 \pm 0.08$ | 21.78 |

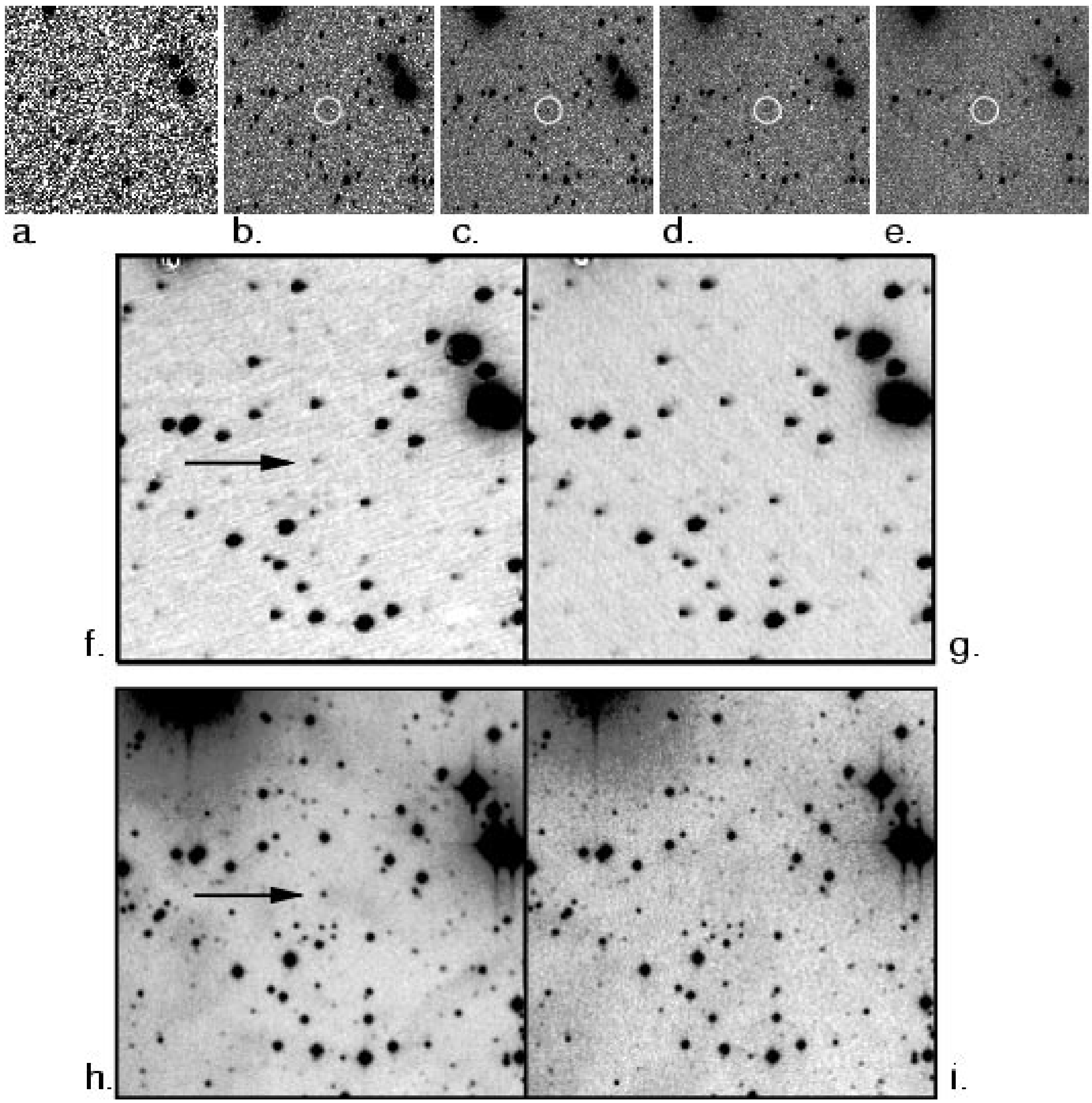


FIG. 1.— Top Panels: SDSS PT images of the afterglow of GRB010921 in $u', g', r', i'$, and $z'$ (from left to right) taken on September 22 UT beginning at 22.108 UT. Middle Panels: Super-LOTIS co-added images in unflitered light taken on September 22 UT beginning at 22.128 UT (left image) and at 22.267 (right image). Bottom Panels: Tautenburg images in I taken on September 22 UT (left image) and on October 25 (right image). In all images, North is toward the top, and East is to the left. The field-of-view of each of the images is $4' \times 4'$. The location of the optical afterglow is indicated by circles in the SDSS PT images, and by arrows in the Super-LOTIS and Tautenburg images.

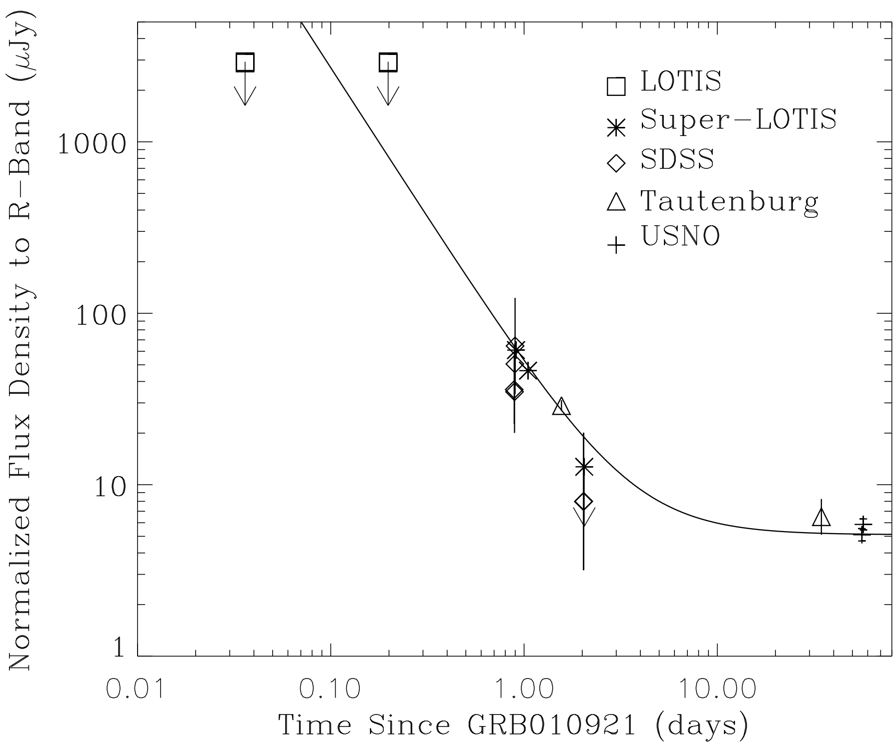


FIG. 2.— The normalized flux density in *R*-band light curve of the afterglow of GRB010921, as constrained by the upper limits from the LOTIS telescope, and the measurements from the SDSS PT, the Super-LOTIS, the Tautenburg Schmidt, and the USNOFS telescopes. The fluxes in the different filters have been transformed to the R-band assuming a power-law spectrum of index $\beta = -2.3$ (Price et al. 2001).