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EVIDENCE FOR A SUPERNOVA IN REANALYZED OPTICAL AND NEAR-INFRARED IMAGES OF GRB 970228

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ABSTRACT

We present *B*-, *V*-, R_C-, I_C-, *J*-, *H*-, *K*-, and *K*′-band observations of the optical transient (OT) associated with GRB 970228, based on a reanalysis of previously used images and unpublished data. In order to minimize calibration differences, we have collected and analyzed most of the photometry and consistently determined the magnitude of the OT relative to a set of secondary field stars. We confirm our earlier finding that the early decay of the light curves (before 1997 March 6) was faster than that at intermediate times (between 1997 March 6 and April 7). At late times the light curves resume a fast decay (after 1997 April 7). The early-time observations of GRB 970228 are consistent with relativistic blast-wave models, but the intermediate- and late-time observations are hard to understand in this framework. The observations are well explained by an initial power-law decay with $\alpha = -1.51 \pm 0.06$ modified at later times by a Type Ic supernova light curve. Together with the evidence for GRB 980326 and GRB 980425, this gives further support for the idea that at least some γ-ray bursts are associated with a possibly rare type of supernova.

Subject headings: gamma rays: bursts — supernovae: general

1. INTRODUCTION

The γ-ray burst (GRB) of 1997 February 28 was the first for which a fading X-ray (Costa et al. 1997) and an optical counterpart (Groot et al. 1997a; van Paradijs et al. 1997) were found. After the counterpart had weakened by several magnitudes, it was found to coincide with an extended object (van Paradijs et al. 1997; Groot et al. 1997b; Metzger et al. 1997a). In subsequent observations with the *Hubble Space Telescope* (*HST*) on 1997 March 26 and April 7, it was found that the optical counterpart consisted of a point source and an extended ($\sim 1''$) object (GAL), offset from the point source by $\sim 0''.5$ (Sahu et al. 1997). The extended object is most likely the host galaxy of GRB 970228, and its redshift was recently determined at $z = 0.695 \pm 0.002$ (Djorgovski et al. 1999). The original light curve was compiled from data taken from the literature (Galama et al. 1997). Data obtained until 1997 April suggested a slowing down of the decay of the optical brightness. The initial behavior of the source appears to be consistent with the relativistic blast-wave model, but the subsequent decrease in rate of fading is harder to explain (Galama et al. 1997). However, the *HST* observations of 1997 September (Fruchter et al. 1997, 1999; Castander & Lamb 1999a) showed that after 1997 April the light curve of the point source roughly continued a power-law decay.

We have gathered and reanalyzed most of the published photometric data on GRB 970228. Previously, this photometric information was drawn from the literature and presented by Galama et al. (1997). We have also gathered yet unpublished images. We analyze the entire data set in an internally consistent way and present here revised Cousins *V*-, R_C-, and I_C-band optical light curves and spectral flux distributions of the γ-ray burst counterpart (§§ 2, 2.1, 3, and 4). We confirm the result of Galama et al. (1997) that the early decay of the light curves (before 1997 March 6) was faster than that at later times (between 1997 March 6 and April 7) and discuss the observations in terms of the relativistic blast-wave and blast-wave plus underlying supernova models in § 5. We find that the observations are well explained by an initial power-law decay with $\alpha = -1.51 \pm 0.06$ modified at later times by a Type Ic supernova light curve. This is in agreement with a recent result of Reichart (1999). Together with similar evidence for GRB 980326 (Bloom et al. 1999), GRB 980425/SN 1998bw (Galama et al. 1998), and perhaps GRB 970514/SN 1997cy (Germany et al. 2000), this gives further support for the idea that at least some GRBs are associated with a possibly rare type of supernova.

2. REANALYSIS OF PREVIOUS OBSERVATIONS

We collected and analyzed most of the photometry of GRB 970228. In Table 1 we provide a log of all the photometry on GRB 970228, obtained in the *B*, *V*, R_C, and I_C

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TABLE 1

SUMMARY OF OPTICAL OBSERVATIONS

Date (UT)	Telescope	Magnitude	Remarks
1997 Feb 28.81	RAO	$R_C = 20.0 \pm 0.5$	Unfiltered OT+GAL
1997 Feb 28.83	BUT	$R_C = 20.58 \pm 0.28$	OT+GAL
1997 Feb 28.99	WHT	$V = 21.01 \pm 0.10$	OT+GAL
1997 Feb 28.99	WHT	$I_C = 20.51 \pm 0.21$	OT+GAL
1997 Mar 03.10	APO	$B_J = 24.5 \pm 0.7$	OT+GAL
1997 Mar 03.90	NOT	$R_C > 22.70 \pm 0.20$	Unfiltered OT+GAL
1997 Mar 04.86	NOT	$R_C = 23.28 \pm 0.40$	Unfiltered OT+GAL
1997 Mar 04.87	NOT	$V > 23.96 \pm 0.12$	OT+GAL
1997 Mar 04.89	NOT	$B > 23.87 \pm 0.10$	OT+GAL
1997 Mar 06.32	Keck	$R_C = 23.60 \pm 0.22$	OT+GAL
1997 Mar 08.86	INT	$V > 24.00 \pm 0.10$	OT+GAL
1997 Mar 08.88	WHT	$I_C > 22.68 \pm 0.10$	OT+GAL
1997 Mar 08.89	INT	$R_C > 23.35 \pm 0.08$	OT+GAL
1997 Mar 09.85	INT	$B = 25.43 \pm 0.31$	OT+GAL
1997 Mar 09.89	INT	$R_C = 23.75 \pm 0.28$	OT+GAL
1997 Mar 13.00	NTT	$R_C = 24.36 \pm 0.15$	OT+GAL
1997 Mar 17.84	CA	$J > 21.45 \pm 0.15$	OT+GAL
1997 Mar 17.83	CA	$H > 20.02 \pm 0.15$	OT+GAL
1997 Mar 17.81	CA	$K' > 20.13 \pm 0.15$	OT+GAL
1997 Mar 26.38	*HST*	$V = 25.98 \pm 0.22$	OT
1997 Mar 26.47	*HST*	$I_C = 23.76 \pm 0.11$	OT
1997 Mar 30.27	Keck	$K = 22.85 \pm 0.25$	OT+GAL
1997 Mar 30.30 + 31.26	Keck	$J = 23.27 \pm 0.15$	OT+GAL
1997 Apr 05.76	Keck	$R_C = 24.97 \pm 0.25$	OT+GAL
1997 Apr 07.22	*HST*	$V = 26.36 \pm 0.26$	OT
1997 Apr 07.30	*HST*	$I_C = 24.10 \pm 0.15$	OT
1997 Mar 26 + Apr 7	*HST* WFPC2	$V = 25.75 \pm 0.35$	GAL
1997 Mar 26 + Apr 7	*HST* WFPC2	$I_C = 24.7 \pm 0.5$	GAL
1997 Sep 04	P5m	$R = 25.5 \pm 0.5$	GAL
1997 Sep 04.71	*HST* STIS	$V = 28.80 \pm 0.40$	OT
1997 Sep 04.71	*HST* STIS	$R_C = 27.69 \pm 0.40$	OT
1997 Sep 04.71	*HST* STIS	$I_C = 26.54 \pm 0.40$	OT
1997 Sep 04.71	*HST* STIS	$V = 25.77 \pm 0.20$	GAL
1997 Sep 04.71	*HST* STIS	$R_C = 25.22 \pm 0.20$	GAL
1997 Sep 04.71	*HST* STIS	$I_C = 24.73 \pm 0.20$	GAL
1998 Sep 01.35	VLT-UT1	$B > 26.08 \pm 0.08$	GAL
1998 Sep 01.35	VLT-UT1	$V > 25.33 \pm 0.05$	GAL
1998 Sep 01.35	VLT-UT1	$R_C > 25.29 \pm 0.06$	GAL

NOTES.—Upper limits are 3 σ. OT: optical transient; GAL: host galaxy; RAO: Rome Astrophysical Observatory; BUT: Bologna University Telescope; WHT: William Herschel Telescope; APO: Apache Point Observatory; NOT: Nordic Optical Telescope; INT: Isaac Newton Telescope; CA: Calar Alto 3.5 m telescope; *HST*: *Hubble Space Telescope*; P5m: Palomar 200 inch; VLT-UT1: Very Large Telescope Unit 1.

passbands (corresponding to the Johnson B and Cousins VRI systems); some photometry derived from unfiltered passbands and translated to B or R_C; the *HST* WFPC2 and STIS filters; and the near-infrared J, H, K, and K' passbands. In order to minimize calibration differences as a result of use of different filters/instruments and differences in analysis, we consistently determined the magnitude of the optical transient (OT) relative to our calibration, which is described in § 2.1, using a set of secondary field stars (Table 2). In §§ 2.2 and 2.3, we discuss each observation separately.

2.1. *Calibration*

As part of the ESO Very Large Telescope Unit 1 (VLT-UT1) Science Verification (1998), a series of deep images of the GRB 970228 field were obtained in B, V, and R_C (see Table 1). The images were bias-subtracted and flat-fielded in the standard fashion. Through the entire night, observations of the Landolt fields SA 99 (around star 253), PG 1633+099, MARK A, and TPHE (Landolt 1992) were obtained allowing accurate photometric calibration for a number of reference stars (see Table 2). We determined the transformation of the reference stars' magnitude to the Landolt system by fitting for the zero point and the first-order extinction and color coefficients.

We also determined a calibration in B, V, and R_C from observations of the Landolt fields SA98 (around star 978), PG 0918+029, and Rubin 149, taken as part of the Isaac Newton Telescope (INT) observations of 1997 March 8 and March 9 (see Table 1). These two calibrations agree, for stars C–H, to within 0.04, 0.02, and 0.10 mag for B, V, and R_C, respectively. The difference between the two calibrations is due to lesser depth of the INT calibration, and we estimated that the absolute calibration uncertainty in each filter from the VLT-UT1 observations is 0.05 mag. We used the VLT-UT1 magnitudes for the reference stars C–H and included stars A and B from the INT calibration (stars

TABLE 2

B, V, R_C, I_C MAGNITUDES; ASSOCIATED RANDOM ERRORS ΔB, ΔV, ΔR_C, ΔI_C; AND THE COORDINATES OF THE REFERENCE STARS

Parameter	A	B	C	D	E	F	G	H
B	21.693	19.614	23.161	23.654	22.296	23.976	...	...
ΔB	0.022	0.010	0.042	0.060	0.016	0.073	...	...
V	20.345	18.793	21.782	21.972	20.648	22.137	23.237	23.003
ΔV	0.011	0.010	0.017	0.021	0.010	0.023	0.064	0.044
R_C	19.646	18.413	20.874	21.119	19.640	20.889	23.008	21.906
ΔR_C	0.040	0.040	0.025	0.032	0.010	0.035	0.103	0.067
I_C	18.787	17.758	20.099	20.501	18.665	19.279	...	20.923
ΔI_C	0.034	0.034	0.045	0.062	0.034	0.040	...	0.080
R.A. (J2000) (5 01+)	48.9	49.3	47.8	48.7	45.9	45.6	47.4	46.4
Decl. (J2000) (11+)	45 59	45 43	46 56	47 01	47 12	47 24	46 56	46 54

NOTES.—We estimate the absolute calibration uncertainty to be 0.05 mag in B, V, and R_C and 0.10 mag in I_C. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

A and B are not contained in the field of the VLT-UT1 images), correcting for the small zero-point offset between the VLT-UT1 and INT calibrations. The adopted reference stars' magnitudes are listed in Table 2.

Observations of the field of GRB 970228 in B, V, R_C, and I_C (for 240 s each filter) and of Landolt field SA 98 were obtained 1999 March 2 with the 1 m Jacobus Kapteyn Telescope (JKT; La Palma). Of stars A–H, only star B was well detected, because of the lesser depth of the JKT images. Therefore, to obtain the I_C-band calibration, we proceeded as follows. First, we determined the magnitudes of star B and six more bright stars in the field of GRB 970228, correcting for the zero point, for the atmospheric extinction, and also for a first-order color term. We then used the I_C-band calibration of these bright field stars to calibrate stars A–H using the William Herschel Telescope (WHT) 1997 March 8 I_C-band image; these magnitudes are listed in Table 2. For consistency, the calibration in B, V, and R_C for star B is in good agreement with the calibration determined from the VLT-UT1 and INT data (better than 0.07 mag).

Near-infrared images in the J and K bands of the field of GRB 970228 and of standard star FS 14 (Casali & Hawarden 1992) were obtained on 1997 March 30.2 UT with the Near Infrared Camera (NIRC) at the Keck I 10 m telescope. From these observations, we obtained a calibration of the nearby star (star H); we found $J = 20.27 \pm 0.10$ and $K = 19.67 \pm 0.10$. Another set of near-infrared images of the field of GRB 970228 and of standard star HD 84800 (Casali & Hawarden 1992) were obtained in J, H, and K' with the Calar Alto 3.5 m telescope on 1997 March 17.8 UT. From these observations, we found for the nearby star (star H) $J = 20.20 \pm 0.15$, $H = 19.16 \pm 0.15$, and $K' = 19.59 \pm 0.28$. The two calibrations are in good agreement with each other, and we adopted their weighted averages: $J = 20.25 \pm 0.10$, $H = 19.16 \pm 0.15$, and $K = 19.66 \pm 0.10$.

2.2. *The Details of Each Observation*

The earliest image of the OT was reported by Pedichini et al. (1997). The reported magnitude was given relative to the nearby late-type star (LTS; star H in Table 2). This observation was obtained without a filter; we have transformed this unfiltered magnitude to the R_C band, using the reported filter characteristics (Pedichini et al. 1997), taking $V - I_C = 0.50 \pm 0.23$ (from the 1997 February 28.99 UT WHT observations) and assuming a power-law spectrum $F_\nu \propto \nu^\beta$. The resulting value $R_C = 20.0 \pm 0.5$ is consistent with that reported by Pedichini et al. (1997) and Galama et al. (1997).

In the images of Guarnieri et al. (1997),[14] the OT was blended with the nearby late-type star. We analyzed their 1997 February 28.83 UT R_C-band image and used a large aperture to include both the OT and the late-type star. The resulting magnitude $R_C = 20.30 \pm 0.28$ (OT+GAL+LTS) in our calibration is about 0.8 mag brighter than that reported by Guarnieri et al. (1997); correcting for the LTS, we found $R_C = 20.58 \pm 0.28$ (OT+GAL). We have not included the subsequent measurements and upper limits as given by Guarnieri et al. (1997) as they are consistent with detections of the late-type star only.

Reanalysis of our WHT, INT, and New Technology Telescope (NTT; La Silla) images have led to marginal corrections; all corrections, apart from the V band 1997 February 28 (which is 0.3 mag off), are within the errors as presented in Galama et al. (1997). We also present an unpublished R_C-band nondetection (INT 1997 March 8.89 UT).

The 1997 March 3.1 UT observation by Margon et al. (1997) with the Astrophysical Research Consortium's 3.5 m telescope at the Apache Point Observatory (APO) was performed using an unfiltered (UF) passband (blue). As the OT was faint in the APO image, we determined its position relative to a number of nearby field stars in the 1997 February 28.99 UT V-band WHT image (where the OT is bright) and performed a rotation plus translation to obtain the corresponding pixel position in the APO image; subsequently, we have used this position to center the aperture to determine the OT's magnitude (the aperture was chosen such that the extended emission was also contained). The unfiltered OT's magnitude was translated to the B passband by fitting an empirical linear relation between the UF$-B$ magnitude difference and the $B-V$ magnitude difference determined from the reference stars A–H (Table 2). We found UF$-B = 24.03(65) + 0.45(11)(B-V)$ ($\chi^2 = 1.2$ with 3 degrees of freedom [dof]). We obtained a rough estimate of the color of the OT by fitting a temporal power-law decay, $F_\nu \propto t^{-\alpha}$, to the V-band data, interpolating the fit to 1997 March 9.85 UT and using the B-band measurement at that same epoch; we found $B-V = 1.10 \pm 0.34$ on 1997 March 9.85 UT. Assuming that the color of the OT did not substantially change, this corresponds to $B = 24.5 \pm 0.7$ on

[14] Note that in Galama et al. 1997 the time of the observation of Guarnieri et al. 1997 is given incorrectly.

1997 March 3.1 UT. (Note that the error is not dominated by the assumed color.) This is about 1.4 σ different from the original value (Margon et al. 1997).

Apart from the 1997 March 4.9 UT V-band image (presented by Galama et al. 1997), additional—and yet unpublished—unfiltered (red) and B-band images were obtained with the Nordic Optical Telescope (NOT). The OT was clearly detected in the unfiltered 1997 March 4.9 UT image but not in the V- and B-band images of 1997 March 4.9 UT nor in the unfiltered image of 1997 March 3.9 UT. Similar to the procedure for the APO data, we determined the pixel position of the OT from the February 28.99 V-band WHT image to obtain the magnitude of the OT in the unfiltered NOT 1997 March 4.9 UT image. The unfiltered OT's magnitude was translated to the R_C passband by fitting an empirical linear relation between UF $-R_C$ and $V-R_C$ determined from the reference stars A–I (Table 2). We found $R_C = 22.97(26) + 0.48(16)(V-R_C)$ ($\chi^2 = 4.3$ with 6 dof). Taking $V-R_C = 1.03$ (corresponding to $V-I_C = 2.24 \pm 0.14$, as observed for the OT with the *HST* 1997 March 26 and April 7; see below), we found $R_C = 23.46 \pm 0.32$. In a similar way, for $V-I_C = 0.50 \pm 0.23$ (WHT 1997 February 28.99) we obtained $R_C = 23.10 \pm 0.27$; we adopted the mean value $R_C = 23.28 \pm 0.40$. Using the same empirical relation between UF$-R_C$ and $V-R_C$, we obtained $R_C > 22.7 \pm 0.2$ for the unfiltered 1997 March 3.9 UT image (using a conservative $V-I_C = 2.24$).

We also determined the pixel position of the OT to obtain its magnitude in the Keck images of 1997 March 6.3 and April 5.8 UT, using again the 1997 February 28.99 UT V-band WHT image. We found the March 6.3 R_C magnitude, relative to our calibration, to be 0.4 mag brighter than that reported by Metzger et al. (1997a); the April 5.8 magnitude is consistent with that reported by Metzger et al. (1997b).

We have not analyzed the Palomar 200 inch 1997 September 4 observation of Djorgovski et al. (1997); it is consistent with detection of the nebulosity only.

We reanalyzed the GRB 970228 *HST* WFPC2 (F606W and F814W) 1997 March 26 and April 7 and STIS 1997 September 4 images of Fruchter et al. (1999). For the details of the observations, we refer the reader to that work. We determined the WFPC2 magnitudes of the OT and stars C, G, and H, using a 2 pixel aperture radius. We corrected the instrumental magnitudes for (1) the "long versus short anomaly" (Casertano and Mutchler 1998; corrections are -0.16, -0.24, -0.12, and -0.19 mag for the WFPC2 observations of March 26 [V], April 7 [V], March 26 [I], April 7 [I], respectively), (2) the effect of nonoptimal charge transfer efficiency (CTE; Whitmore & Heyer 1997; Whitmore 1998; corrections are ~ -0.06 mag), and (3) the geometric distortion of WFPC2 images (Holtzman et al. 1995a; corrections are smaller than 0.03 mag). Next, we determined the aperture correction from 2 to 11 pixels and used the instrumental zero points from Baggett et al. (1997) and the color corrections from Holtzman et al. (1995b) to obtain the final V- and I_C-band magnitudes. The errors were determined by adding in quadrature the measurement error (Poisson noise), the errors in the above-mentioned corrections, the aperture correction error, and a 2% uncertainty for the instrumental zero points. For the OT the error in the magnitude is dominated by the long versus short anomaly correction (the correction is larger for fainter objects). The results for the OT are given in Table 1. We found systematically brighter magnitudes than Fruchter et al. (1999) and Castander & Lamb (1999a), which can be explained by the long versus short anomaly correction that we applied. We found the OT to be redder ($V-I_C = 2.22 \pm 0.25$ and $V-I_C = 2.26 \pm 0.30$, 1997 March 26 and April 7 UT, respectively) than found by Fruchter et al. (1999) but consistent with the result of Castander & Lamb (1999a). For stars C, G, and H, we obtained (V, I_C) = (21.76 ± 0.05, 20.10 ± 0.05), (23.46 ± 0.05, 22.52 ± 0.07) and (22.85 ± 0.04, 21.04 ± 0.04), respectively. Comparing this with the ground-based calibration (see Table 2), we found the agreement for the bright star C to be excellent (better than 0.02 mag), for star H we found 0.15 and 0.12 mag differences, and the V-band *HST* magnitude of star G was 0.22 mag off.

The *HST* STIS observations were taken in unfiltered mode, meaning that the response covers a wide wavelength range from about 2000 to 10000 Å. To convert the observed counts into broadband magnitudes, we had to assume, therefore, something about the spectral energy distribution. Our procedure was as follows: (1) measure the counts in a 2 pixel radius aperture; (2) add an aperture correction of -1.15 mag based on brighter stars in the field, assuming that 10% of the light falls outside a large 11 pixel radius aperture; (3) assume a power-law slope with spectral index chosen to be consistent with the earlier WFPC2 observations ($\beta = -4.7$); and (4) use the SYNPHOT routine CALCPHOT to determine the corresponding broadband magnitudes to explain the observed counts. The result, corrected for the small 12% renormalization found by Landsman (1997), was $V = 28.80$, $R_C = 27.69$, and $I_C = 26.54$. Although the uncertainty in the measured counts is only 10%, the considerable dependence on the shape of the assumed spectrum, and the difficulty of absolutely calibrating the wide STIS passband (see below), leads us to adopt an uncertainty of 0.4 mag for each band (for example, changing the assumed spectral slope β by ± 1 σ leads to $^{+0.37}_{-0.32}$, $^{+0.17}_{-0.11}$, and $^{+0.02}_{-0.06}$ mag differences in the V-, R_C- and I_C-band magnitudes, respectively). Because the assumed spectrum is very red, most of the flux is in the R_C and I_C passbands and the inferred V-band magnitude is less well constrained. We also note that assumption 3 is not necessarily correct. But, for now, in view of the limited amount of information available on the spectral reddening evolution of the OT, we use this minimal assumption. Note also that we drop this assumption in the discussion (§ 5), where we assume a spectral flux distribution given by a template redshifted supernova; the results for both assumptions are, however, very similar.

To check the STIS result, we tried an alternative calibration using our WFPC2 photometry for the two brightest field stars, but still relying on SYNPHOT to calculate the appropriate color correction, and found a STIS magnitude of $V = 28.58$. This discrepancy is larger than the formal errors and is probably indicative of the difficulty of precisely calibrating the very wide unfiltered STIS CCD passband.

We collected and rereduced the near-infrared J- and K-band images of Soifer et al. (1997), obtained on 1997 March 30.2 and 31.2 UT with NIRC on the Keck I 10 m telescope, and the J-, H-, and K'-band images of Klose, Stecklum, & Tuffs (1997), obtained with the Calar Alto 3.5 m telescope on 1997 March 17.8 UT using the near-infrared camera MAGIC. The infrared frames were reduced

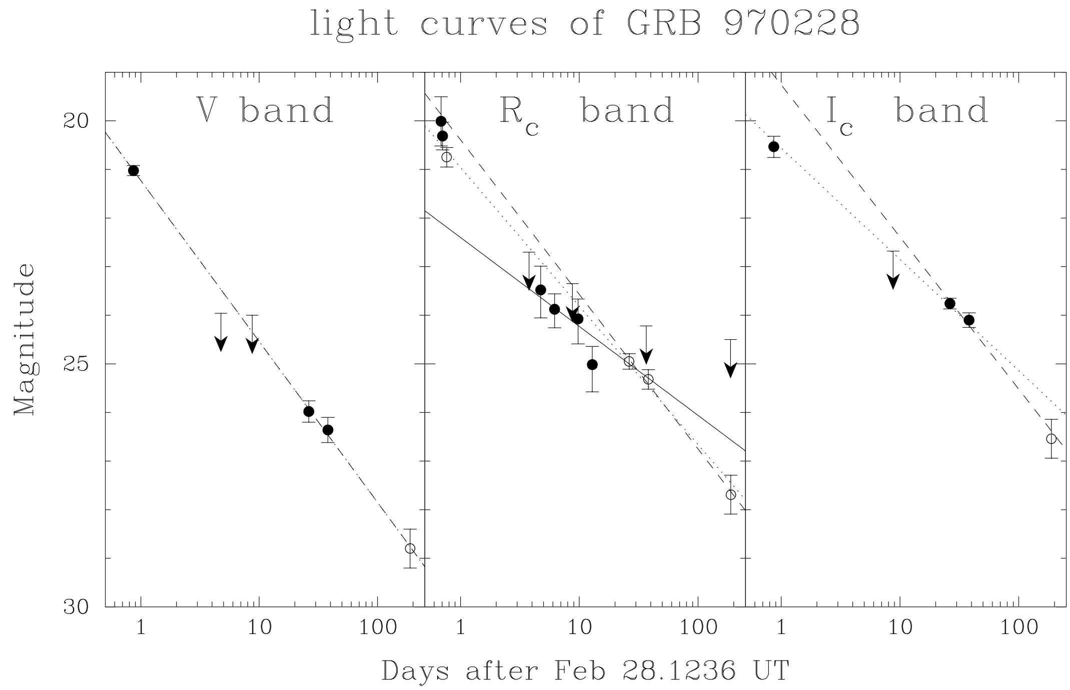

FIG. 1.—V-, R_C-, and I_C-band light curves of GRB 970228 (magnitude vs. time). Data obtained from interpolations between V and I_C or data obtained from the wide *HST* STIS filter are indicated with open symbols (see the discussion for details). Indicated are power-law fits, $F_\nu \propto t^\alpha$, to the detections (ignoring upper limits). Fits to all points are indicated by the dotted lines and fits to the late-time light curve (after 20 days) are indicated by the dashed lines (for the V band, the overlap). Also indicated is a fit to the R_C-band light curve at intermediate times (between 3 and 50 days; *thick line*).

by first removing bad pixels and combining at least five frames around each object image to obtain a sky image. This sky image was then subtracted after scaling it to the object image level.

A source was detected both in band J and in band K in the Keck I observations. Relative to the nearby star (star H), we found $J = 23.27 \pm 0.15$ (OT+GAL; sum of the 1997 March 30.3 and 31.2 UT data) and $K = 22.85 \pm 0.25$ (1997 March 30.2 UT) within a large 0".75 aperture radius. The J-band magnitude is consistent with the earlier determination (Soifer et al. 1997), but our K-band determination is 0.8 mag fainter. Fruchter et al. (1999) detected the host galaxy at $K = 22.8 \pm 0.3$, and so our result is consistent with detection of the host galaxy only.

We did not detect the source in the Calar Alto J, H, and K' images and determined the following limiting magnitudes: $J > 21.45$, $H > 20.02$, and $K' > 20.13$ (3 σ). We confirm the nondetections in H and K' by Klose et al. (1997) but do not confirm their detection of the source in J.[15]

2.3. *The Host Galaxy*

The host galaxy of GRB 970228 is clearly detected in the *HST* WFPC2 images, but at a low signal-to-noise ratio. Working with cosmic-ray and hot-pixel cleaned images, we first subtracted point-spread functions positioned and scaled to remove the image of the OT from each. For the two F606W images, we then performed aperture photometry in apertures of increasing size, taking a sky estimate from the surrounding area which was free of other objects. We found that the counts reached an asymptote, within the noise, by a radius of 25 pixels (~1".1). We calibrated this using the procedure of Holtzman et al. (1995b), finding an average $V_{606} = 25.5 \pm 0.3$, where the error is dominated by the photon and read noise.

In the F814W image, the host galaxy is even fainter, and we estimated its color by comparing the counts within a 7 pixel radius aperture with the counts in the same aperture on the F606W image. Thus, we found a color $V_{606} - I_{814} \sim 1.1$ which is, correcting for the Galactic extinction, reasonable for a galaxy at this magnitude (Smail et al. 1995). This could then be used to estimate color corrections to the standard systems, and we concluded $V = 25.75 \pm 0.35$ and $I_C = 24.7 \pm 0.5$.

The host galaxy is much better detected on the STIS image, although we must assume a spectral shape in order to estimate broadband magnitudes. Using CALCPHOT we found a good match to the WFPC2 colors with a suitably redshifted and reddened Sc galaxy spectrum.[16] Based on this, we infer $V = 25.77$, $R_C = 25.22$, and $I_C = 24.73$ from the STIS data, which is in good agreement with the other determinations. We adopt an error of 0.2 mag to account for the systematic uncertainty introduced by the necessity of assuming the spectral shape.

We did not detect the host galaxy of GRB 970228 in the ESO VLT-UT1 Science Verification images and determined the 3 σ limit for detection using an aperture radius of 1.5 times the seeing, which corresponds to ~1".5. The results

[15] The J-band magnitude reported by Klose et al. (1997) is affected by a transient warm pixel at the position of the source that was not obvious in the bad pixel mask.

[16] From the Kinney-Calzetti atlas, see the Synphot User Guide 1998, Space Telescope Science Institute.

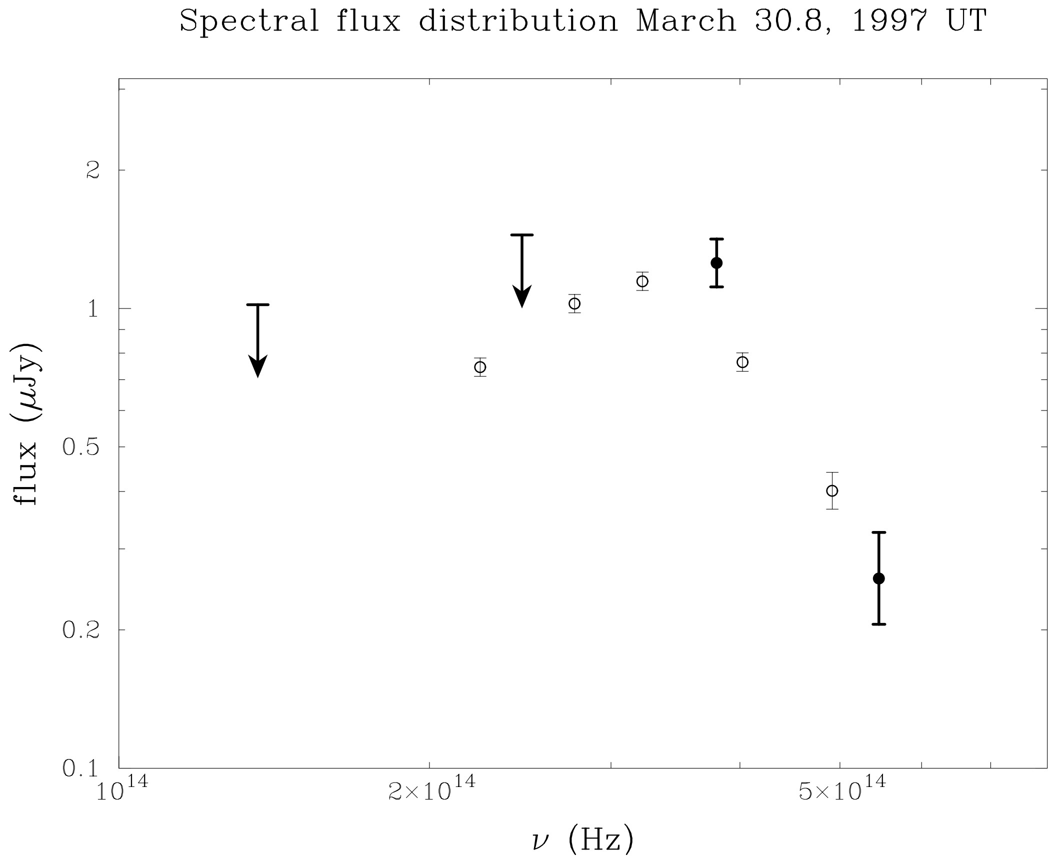

FIG. 2.—Optical/near-infrared spectral flux distribution of GRB 970228 at 1997 March 30.8 UT (*filled circles, upper-limit arrow*). From left to right: K-band detection (Table 1) translated into an upper limit because it is consistent with detection of the host galaxy only (detection magnitude minus 3 σ), J-band detection (Table 1) translated into an upper limit due to unknown J-band host magnitude (detection magnitude minus 3 σ), V and I_C *HST* measurements from Table 1. Also shown is the spectral flux distribution of SN 1998bw redshifted to the redshift of GRB 970228 (*open circles*). Note that the spectral flux distribution is different from that of Reichart (1999) (see the discussion in § 4).

are shown in Table 1. The V- and R_C-band upper limits for the host galaxy show that the host galaxy is fainter than the earlier determination (Sahu et al. 1997) but consistent with the results of Fruchter et al. (1999), Castander & Lamb (1999a), and our estimate from the WFPC2 images.

3. THE LIGHT CURVES

In the interpolations to the R_C band (see Fig. 1), we have assumed that the spectra of both the point source and the host galaxy are smooth (i.e., not dominated by emission lines). We have used the relation between the color indices $V-R_C$ and $V-I_C$ given by Thé, Steenman, & Alcaino (1984) for late-type stars; for bluer stars we have inferred this relation from the tables given by Johnson (1966) for main-sequence stars and the color transformations to the Cousins *VRI* system given by Bessel (1976). We have tested the validity of these color-color relations from numerical integrations of power-law flux distributions and of Planck functions and conclude that if the flux distributions of the OT and the host galaxy are smooth the uncertainty in the interpolated R_C magnitude is unlikely to exceed 0.1 mag (Galama et al. 1997). For the *HST* 1997 September 4 observation, we have assumed that the colors of the OT remained constant during the late-time decay (i.e., taking the observed $V-I_C = 2.24$ from the *HST* 1997 March 26 and April 7 observations; see § 2.2). Finally, we corrected for the contribution of the host galaxy emission ($V = 25.77 \pm 0.20$, $R_C = 25.22 \pm 0.20$, and $I_C = 24.73 \pm 0.20$) and obtained the V-, R_C-, and I_C-band light curves of the OT (Fig. 1).

We have fitted power laws, $F \propto t^{\alpha}$, to the light curves (ignoring upper limits) and found $F_V = (11.7 \pm 1.0) t_d^{-1.32 \pm 0.04}$ μJy ($\chi^2 = 0.2$ with 2 dof), $F_{R_C} = 12.7^{+1.2}_{-1.8} t_d^{-1.14 \pm 0.04}$ μJy ($\chi^2 = 9.7$ with 8 dof), and $F_{I_C} = 15.2^{+3.1}_{-2.5} t_d^{-0.92 \pm 0.06}$ μJy ($\chi^2 = 4.5$ with 2 dof), where t_d is the time in days. These fits are indicated with dotted lines in Figure 1. We also fitted a power law to the R_C-band light curve at intermediate times (between 3 and 50 days) and found $F_{R_C} = 3.4^{+2.4}_{-1.4} t_d^{-0.73 \pm 0.17}$ μJy ($\chi^2 = 1.3$ with 4 dof). The fit is indicated with a thick line in Figure 1. For the late-time detections (after 20 days), we found $F_V = (11.7 \pm 1.3) t_d^{-1.14 \pm 0.21}$ μJy ($\chi^2 = 0.2$ with 1 dof), $F_{R_C} = 21.5^{+23}_{-11} t_d^{-1.27 \pm 0.20}$ μJy ($\chi^2 = 0.3$ with 1 dof) and $F_{I_C} = 50^{+48}_{-24} t_d^{-1.25 \pm 0.19}$ μJy ($\chi^2 = 0.9$ with 1 dof), where t_d is the time in days. These fits are indicated with dashed lines in Figure 1.

4. OPTICAL/NEAR-INFRARED TO X-RAY SPECTRA

For three epochs we have reconstructed the spectral flux distribution of the OT, corresponding to (1) 1997 February 28.99 UT (V, R_C, and I_C data from Table 1 and 2–10 keV flux from Costa et al. 1997), (2) March 9.89 UT (R_C-band measurement from Table 1 and *ROSAT* 0.1–2.4 keV unabsorbed flux from Frontera et al. 1998), and (3) March 30.8 UT (see Fig. 2). We subtracted the host galaxy flux from ground-based measurements; corrected the OT fluxes for Galactic foreground absorption, $A_V = 0.78 \pm 0.12$ (from Schlegel, Finkbeiner, & Davis 1998; but see also the discussion by González, Fruchter, & Dirsch 1999 and Castander & Lamb 1999b); and brought measurements to the same epoch using the power-law fits of § 3. We note that the spectral flux distribution on March 30.8 UT (Fig. 2) is different from that of Reichart (1999) because in our reanalysis the optical transient was not detected in the K band. The resulting spectral flux distribution therefore supersedes that of Reichart (1999), who obtained the K-band magnitudes of the OT and the host from the literature.

We fitted the optical to X-ray spectral flux distribution of the first epoch (1997 February 28.99 UT) with a power law and an exponential optical extinction law, $F_\nu \propto \nu^\beta e^{-\tau}$, where we assumed that the extinction optical depth $\tau \propto \nu$. The data did not allow determination of the host galaxy extinction; the fit provided a negative extinction ($A_V < 0.50$; 90% confidence) and was subsequently fixed at zero. We found a spectral slope, $\beta = -0.780 \pm 0.022$ (reduced χ^2, $\chi_r^2 = 4/2$). For comparison, the X-ray power-law photon index observed ~ 12 hours after the burst (2–10 keV; Costa et al. 1997) corresponds to a spectral slope $\beta = -1.1 \pm 0.3$.

5. DISCUSSION

Most X-ray and optical/infrared afterglows display a power-law temporal decay; this is a prediction for relativistic blast-wave models of GRB afterglows, in which a relativistically expanding shock front, caused by an energetic explosion in a central compact region, sweeps up the surrounding medium and accelerates electrons in a strong synchrotron emitting shock (e.g., Mészáros & Rees 1997). Assuming a single power law and ignoring upper limits for the moment, the V-, R_C-, and I_C-band light curves (Fig. 1) indicate that the power-law decay rate is an increasing function of frequency; for the V, R_C, and I_C band, the power-law decay index $\alpha = -1.32 \pm 0.04$, -1.14 ± 0.04, and -0.92 ± 0.06, respectively. This implies that as a function of time the OT becomes redder and redder. Such a relation has not been observed previously and is not what is expected in standard relativistic blast-wave models, where the power law index is, to first order, independent of frequency.

Taking the upper limits into account, we find that the 1997 March 4.87 UT NOT V-band nondetection is significantly below the fit. Also, the R_C-band light curve suggests that the optical emission is weaker around that time (between 3 and 10 days) than expected from a single power law. The V and R_C data suggest that the initial decline was faster than the decline at intermediate times. From the V-band 1997 February 28.99 and March 4.87 UT data, we find that the early-time decay was steeper than $\alpha = -1.4$ ($3\ \sigma$), while at intermediate times (around 10 days) it was $\alpha = -0.73 \pm 0.17$ (R_C). This structure in the light curve was recognized early on by Galama et al. (1997), who showed that the early decay of the light curves (before 1997 March 6) was faster than that at later times (between 1997 March 6 and April 7). The earlier analysis of the 1997 March 26 and April 7 *HST* WFPC2 images yielded brighter estimates of the host galaxy magnitudes (Sahu et al. 1997) than our reanalysis (see also Fruchter et al. 1999; Castander & Lamb 1999a). Because of this, the correction to the ground-based data for the host galaxy emission applied in this work is smaller than that of Galama et al. (1997), and thereby the effect is somewhat reduced, but it is still present (see also Reichart 1999) and consistent with the earlier result.

The late-time light curves show that the rate of decay increased again after ~ 35 days. The late-time decays in V, R_C, and I_C are consistent with being frequency independent (i.e., similar decays in V, R_C, and I_C), with a power-law index $\alpha = -1.2$. The back extrapolation of the late-time fit in the V band predicts quite well the earliest V-band data, but this is not the case for the R_C- and I_C-band light curves. We conclude that a single power law is not a good representation of the light curves; the overall shape of the light curves is that of an initial fast decay (before ~ 1997 March 6), followed by a "plateau" (slow decay; between ~ 1997 March 6 and $\sim$April 7), and finally the light curves resume a fast decay (after ~ 1997 April 7).

For synchrotron radiation, by a power-law energy distribution of electrons, at low frequencies, and for an adiabatic evolution of the blast wave, we can distinguish the following two cases, each of which has its own relation between the spectral slope β and the power-law decay index α (Sari, Piran, & Narayan 1998). (1) Both the peak frequency ν_m and the cooling frequency ν_c are below the optical wave band. Then $\alpha = 3\beta/2 + \frac{1}{2} = -0.67 \pm 0.03$ (taking the measured spectral slope $\beta = -0.78$ on 1997 February 28.99 UT). (2) Alternatively, ν_m has passed the optical wave band, but ν_c has not yet. In that case $\alpha = 3\beta/2 = -1.17 \pm 0.03$. The temporal decay values measured at early times are in reasonable agreement with case 2 but certainly not with case 1, suggesting that the peak frequency ν_m is below the optical passband and that the cooling frequency ν_c is near or above the X-ray (2–10 keV) passband; such a high cooling frequency appears to be the fairly general case in GRB afterglows (e.g., Bloom et al. 1998; Vreeswijk et al. 1999; Galama et al. 1999). The fit to the optical to X-ray spectrum of 1997 February 28.99 UT suggests that extinction at the host is not very significant ($A_V < 0.5$; corresponding to a rest-frame extinction $A_V < 0.3$). At the second epoch, we measured a spectral slope, $\beta = -0.52 \pm 0.08$, on 1997 March 9.89 UT. For case 2 this would correspond to a power-law decay of $\alpha = -0.78 \pm 0.12$, consistent with a shallower decay at intermediate times. We thus find that the observations of the early-time afterglow are roughly consistent with the predictions of simple relativistic blast-wave models (see also Wijers, Rees, & Mészáros 1997; Waxman 1997; Reichart 1997), except that we find evidence for a flattening of the decay rate around 10 days.

As mentioned above, the frequency dependence of the rate of decay of the light curves corresponds to a reddening of the optical afterglow with time ($V - I_C = 0.50 \pm 0.23$ at 1997 February 28.99 UT and $V - I_C = 2.24 \pm 0.14$ at 1997 March 26 and April 7). We are confident about this large change in color as the *HST* calibration of three field stars agrees well with that of the ground-based calibration. Assuming a power-law spectrum, the optical spectral slopes (Galactic extinction corrected) from the intermediate-time V and I_C *HST* observations are $\beta = -3.8 \pm 0.7$ (1997 March 26) and $\beta = -4.0 \pm 0.8$ (1997 April 7). These steep spectra cannot be explained by extinction at the host galaxy; we find a staggering $A_V = 4.5 \pm 1.0$ (fitting as before for an exponential optical extinction law, $F_\nu \propto \nu^\beta e^{-\tau}$, with $\tau \propto \nu$, and fixing the spectral slope at $\beta = -0.78$), which would imply that the extinction increased with time from negligible ($A_V < 0.5$) to very significant ($A_V = 4.5 \pm 1.0$); this seems quite unlikely. A steepening of the spectral slope may be expected from a number of spectral transitions, e.g., the passage of the cooling frequency or the transition to a Sedov-Taylor nonrelativistic expansion (e.g., Sari et al. 1998; Waxman, Kulkarni, & Frail 1998). However, such spectral transitions will be accompanied with an increase in the rate of decay of the light, which we do not observe here. The discrepancy is even larger if one considers the spectral flux distribution around the third epoch (1997 March 30.8 UT; Fig. 2); the spectrum shows an unexpected turnover around 3×10^{14} Hz (Fruchter et al. 1999). This break plus the very red spectrum in V and I_C in the intermediate-time optical flux distribution is not consistent with the predictions of simple relativistic blast-wave models (see also Reichart 1999; Fruchter et al. 1999).

What then could explain these observations? Bloom et al. (1999) observed a similarly red spectrum for the late-time emission from GRB 980326. The authors argue that this is due to a supernova (SN) that dominated the light at late times. Reichart's (1999) result suggests that this is also the case for GRB 970228. In this hypothesis the early light curve is dominated by a (power-law decaying) GRB afterglow (produced by the relativistic blast wave), while at late times the light curve contains a significant contribution from an underlying supernova. Such would be the natural outcome of the "collapsar/microquasar" models in which GRBs arise in jets (e.g., Shaviv & Dar 1995) that are formed in the core collapse to a black hole of massive stars (Woosley 1993; Paczyński 1998). Such massive stars will, prior to collapse, have lost their hydrogen envelopes, and so we expect the supernova to be of Type Ib/c (Woosley 1993; Woosley, Eastman, & Schmidt 1999; Bloom et al. 1999). We note however that a priori the SN type of SNe that accompany GRBs is not known.

Following Bloom et al. (1999) and Reichart (1999), we constructed simulated supernova light curves and spectral flux distributions as follows. First, we combined three sets of Galactic extinction-corrected U-, B-, V-, R_C-, and I_C-band observations of the well-observed, unusual Type Ic SN 1998bw (Galama et al. 1998; McKenzie & Schaefer 1999; Vreeswijk et al. 1999), which is likely to be associated with GRB 980425 (Galama et al. 1998; Kulkarni et al. 1998).[17] We then redshifted the light curves to the redshift of GRB 970228, $z = 0.695$ (Djorgovski et al. 1999), which consists of wavelength shifting, time-profile stretching, and dimming (we assumed a cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1} and $\Omega_0 = 1.0$). To obtain the corresponding redshifted light curves in the V, R_C, and I_C bands, we assumed a power-law spectral shape to interpolate (and extrapolate) the redshifted SN 1998bw light curves to the central wavelengths of the V, R_C, and I_C bands. (Note that the redshifted central wavelength of the U band is near V and R_C and for the B band is near I_C.) Finally, we corrected the SN light curves for the Galactic extinction in the direction of GRB 970228 ($A_V = 0.78 \pm 0.12$). These light curves are shown in Figure 3.

The supernova spectral flux distribution corresponding to the epoch of 1997 March 30.8 UT (30.7 days after GRB 970228) is shown in Figure 2 (here we did the opposite: we corrected the GRB 970228 spectral flux distribution for Galactic extinction). The resemblance of the GRB 970228

[17] The association between SN 1998bw and GRB 980425 has been considered uncertain because the behavior of another source in the error box of GRB 980425, the fading X-ray source 1SAX J1935.3−5252, resembled that of a typical GRB afterglow. However, reanalysis of *BeppoSAX* Narrow Field Instrument observations of the GRB 980425 field by Pian et al. (2000) shows that its behavior is unlike that of previously observed GRB afterglows. SN 1998bw remains not typical for GRB afterglows because of its low redshift, $z = 0.0085$.

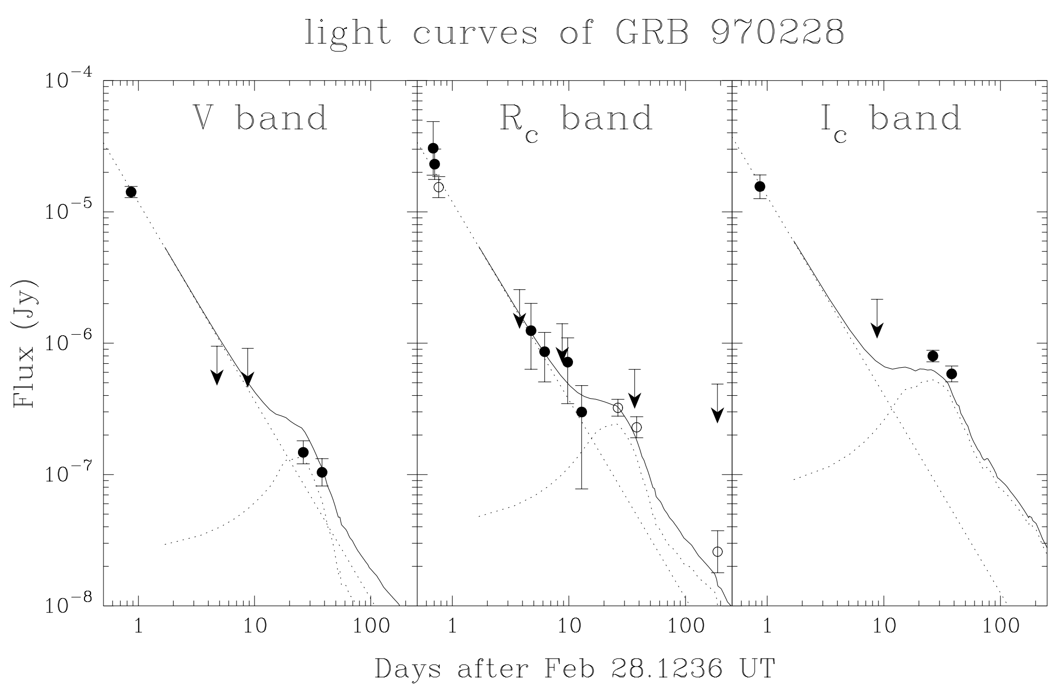

FIG. 3.—V-, R_C-, and I_C-band light curves of GRB 970228 (fluxes vs. time). Data obtained from interpolations between V and I_C or data obtained from the wide *HST* STIS filter are indicated with open symbols (see the discussion for details). The dotted curves indicate power-law decays with $\alpha = -1.51$ and redshifted SN 1998bw light curves. The thick line is the resulting sum of SN and power-law decay light curves.

and the redshifted SN 1998bw spectral flux distributions is remarkable (see also Reichart 1999).

At early times the R_C-band light curve (see Fig. 3) will include negligible contribution from the SN emission. If we attribute the early part ($t < 8$ days) of the R_C-band light curve to GRB afterglow and fit a power-law temporal decay to the data, we find a temporal decay index $\alpha = -1.46 \pm 0.16$ ($\chi^2 = 1.5$ with 3 dof). This value of the decay constant is consistent with that in X-rays, $\alpha = -1.33^{+0.11}_{-0.13}$ during the first $\sim$4 days (2–10 keV; Costa et al. 1997) and $\alpha = -1.50^{+0.35}_{-0.23}$ up to $\sim$10 days (0.1–2.4 keV; Frontera et al. 1998). It is also consistent with the earlier determination (Galama et al. 1997; see also Reichart 1999).

Next, we took a single value for the power-law decay in V, R_C, and I_C, computed the sums of these power-law decays plus supernova light curves, and fitted for the power-law decay index α by minimizing the χ^2 of the V, R_C, and I_C light curves and the resulting fit. But first, the assumption of a constant color that was used to derive a V-band magnitude from the 1997 September unfiltered STIS observation is no longer valid as in this hypothesis at late times the SN emission will dominate the light, and so we expect the light to have reddened (see Fig. 3). Thus, in order to convert the observed counts into broadband magnitudes, we assumed that the spectral energy distribution was similar to that of SN 1998bw, redshifted to $z = 0.695$. Our procedure was as follows: (1) we used the redshifted U, B, V, R_C, and I_C spectral flux distribution of SN 1998bw (on day 128, corresponding to the STIS epoch at 216 days); (2) we corrected for Galactic extinction, $A_V = 0.78 \pm 0.12$, interpolating to the redshifted central wavelengths of the U, B, V, R_C, and I_C bands using the Galactic extinction curve of Cardelli, Clayton, & Mathis (1989) to obtain the spectral flux distribution as it would be observed in the direction of GRB 970228; and (3) we used this spectral flux distribution in the SYNPHOT routine CALCPHOT, and applied the Landsman (1997) correction, to determine corresponding broadband magnitudes, $V = 28.56$, $R_C = 27.42$, and $I_C = 26.43$. Again, we adopt an uncertainty of 0.4 mag to make some allowance for the sensitivity of the result to the assumed spectral shape. Finally, we minimized the χ^2 and found $\alpha = -1.51 \pm 0.06$ ($\chi^2 = 22$ with 14 dof; we note that the χ^2 is not strictly correct since a few of the data points are not independent). The fit is excellent in view of the uncertainties in the model. Similar results were presented by Reichart (1999). The fit is somewhat better than that presented by Reichart (1999), presumably because of our consistent reanalysis of all the original images and, in particular, because our STIS magnitudes were calculated using the knowledge of the spectral shape of the template supernova.

The model has very few assumptions: the power-law index α is the only free parameter, and we did not allow the peak luminosity of the SN to be a free parameter but used the SN 1998bw observations as they are. SN 1998bw is, of course, an unusual example of the class, being very bright and rapidly expanding, but its coincidence with GRB 980425 makes it the only template we can reasonably choose for now. Also, from the "collapsar" model we expect a GRB to be accompanied by a supernova of Type Ib/c. In any case, the light curves (Fig. 3) as well as the intermediate-time spectral flux distribution (Fig. 2) and intermediate-time colors are remarkably well explained by the sum of a power law plus supernova light curve. It can explain the apparent transition from a rapid to a slow and again a rapid decline of the light curves, is in good agreement with the upper limits in the light curves, and it can account for the unusual intermediate-time red color $V - I_C = 2.24$ and the peaked spectral flux distribution on 1997 March 30.8 UT (see also Reichart 1999). These features cannot be accounted for by simple relativistic blast-wave models. We thus find the data to be in agreement with the hypothesis that a supernova dominated the light at late times. Together with the evidence for GRB 980326 (Bloom et al. 1999), GRB 980425/SN 1998bw (Galama et al. 1998), and perhaps GRB 970514/SN 1997cy (Germany et al. 2000), this is further support for the idea that at least some GRBs are associated with a possibly rare type of supernova.

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