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OPTICAL FOLLOW-UP OF GRB 970508

T. J. GALAMA,¹ P. J. GROOT,¹ J. VAN PARADIJS,^{1,2} C. KOUVELIOTOU,^{3,4} R. G. STROM,^{1,5} R. A. M. J. WIJERS,⁶
 N. TANVIR,⁶ J. BLOOM,⁷ M. CENTURION,^{8,9} J. TELTING,⁹ R. G. M. RUTTEN,⁹ P. SMITH,¹⁰ C. MACKEY,¹⁰
 S. SMARTT,⁹ C. BENN,⁹ J. HEISE,¹¹ AND J. IN'T ZAND¹¹

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ABSTRACT

We report on the results of optical follow-up observations of the counterpart of the gamma-ray burst GRB 970508, starting 7 hr after the event. Multicolor *U*-, *B*-, *V*-, *R_c*-, and *I_c*-band observations were obtained during the first three consecutive nights. The counterpart was monitored regularly in *R_c* until ~4 months after the burst. The light curve after the maximum follows a decline that can be fitted with a power law with exponent $\alpha = -1.141 \pm 0.014$. Deviations from a smooth power-law decay are moderate (rms = 0.15 mag). We find no flattening of the light curve at late times. The optical afterglow fluence is a significant fraction, ~5%, of the GRB fluence. The optical energy distribution can be well represented by a power law, the slope of which changed at the time of the maximum (the spectrum became redder).

Subject heading: gamma rays: bursts

1. INTRODUCTION

With the Wide Field Cameras (WFCs; Jager et al. 1993) on board *BeppoSAX* (Piro, Scarsi, & Butler 1995), it became possible for the first time to determine rapidly the accurate (3' radius) gamma-ray burst (GRB) positions (Costa et al. 1997a, 1997b; In't Zand et al. 1997; Heise et al. 1997a); such positions, as it turned out, are the necessary ingredient for successful counterpart searches (see also Takeshima et al. 1998 and Smith et al. 1998). The detection of a fading optical counterpart to GRB 970228 provided the first arcsecond localization of a GRB (Groot et al. 1997a; van Paradijs et al. 1997; Galama et al. 1997, 1998). Its coincidence with a faint extended object (Groot et al. 1997b; Metzger et al. 1997a; Sahu et al. 1997a), which is probably the host galaxy, suggests a cosmological distance for the GRB. A second optical transient (OT) was found for GRB 970508 (Bond 1997). The measurement of a lower bound to the redshift ($z \geq 0.835$; Metzger et al. 1997b) of this optical counterpart has unambiguously settled the cosmological distance scale to GRB sources.

On May 8.904 UT, the Gamma-Ray Burst Monitor (GRBM) on *BeppoSAX* recorded a moderately bright GRB (Costa et al. 1997c), which was also recorded with its Wide Field Cameras. The fluences, recorded with the GRBM (40–700 keV) and a WFC (2–26 keV), were $(1.8 \pm 0.3) \times 10^{-6}$ ergs cm⁻² and $(0.7 \pm 0.1) \times 10^{-6}$ ergs cm⁻², respectively (Piro et al. 1997a).

The burst was also recorded (Kouveliotou et al. 1997) with BATSE (Fishman et al. 1989), with a total 20–1000 keV fluence of $(3.1 \pm 0.2) \times 10^{-6}$ ergs cm⁻² and a peak flux density (50–300 keV) of $(1.66 \pm 0.06) \times 10^{-7}$ ergs cm⁻² s⁻¹. From optical observations of the WFC error box (Heise et al. 1997b), made on May 9 and 10, Bond (1997) found a variable object at R.A. = 06^h53^m49^s.2, decl. = +79°16'19" (J2000), which shows an increase by ~1 mag in the *V* band. *BeppoSAX* Narrow Field Instrument observations revealed an X-ray transient (Piro et al. 1997b) whose position is consistent with that of the optical variable. Extended emission is not associated with this optical counterpart (Fruchter et al. 1997; Sahu et al. 1997b; Pian et al. 1998), and Natarajan et al. (1997) show either that GRB 970508 originated from an intrinsically very faint dwarf galaxy or that it occurred at a large distance from a host galaxy ($>25 h_{70}^{-1}$ kpc).

Here we report on the results of the optical photometry of GRB 970508, made between 0.3 and 110 days after the burst.

2. OPTICAL PHOTOMETRY

We have used the 4.2 m William Herschel Telescope (WHT) at La Palma to make optical observations in *U*, *B*, *V*, *R_c*, and *I_c* of the WFC error box with both the Prime Focus Camera (PF; field of view 9'0 × 9'0) and the Auxiliary Port Camera (AUX; field of view 0'9 radius). All WHT PF exposures lasted 600 s, except the one made on August 26.9 UT, which lasted 1800 s. The WHT AUX exposures were 3600 s each. As part of the Kitt Peak National Observatory Queue observations, observations were also made with the 3.5 m Wisconsin-Indiana-Yale-NOAO (WIYN) telescope, using the WIYN Imager S2KB at the Nasmyth focus. Ten 6'8 × 6'8 *R*-band images were obtained between May 9.15 and 9.23 UT at several pointings in order to cover the whole error box. All exposures lasted 300 s. A log of the observations is shown in Table 1.

We have corrected the *U*- and *B*-band images for the non-linearity at low counts of the LORAL2 CCD chip,¹² used for the May 10, 11, and 12 WHT observations (this effect is negligible in the *V*, *R_c*, and *I_c* observations). We made a photometric calibration (*U*, *V*, *R_c*, and *I_c*) using WHT observations on May

¹ Astronomical Institute "Anton Pannekoek," University of Amsterdam, and Center for High Energy Astrophysics, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands.

² Department of Physics, University of Alabama at Huntsville, Huntsville AL 35899.

³ Universities Space Research Association.

⁴ NASA Marshall Space Flight Center, Code ES-84, Huntsville AL 35812.

⁵ Netherlands Foundation for Research in Astronomy (NFRA), Postbus 2, 7990 AA Dwingeloo, The Netherlands.

⁶ Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, England, UK.

⁷ Caltech, 105-24, Pasadena, CA 91125.

⁸ Instituto de Astrofísica de Canarias, Vía Lactea, E-38200 La Laguna, Tenerife, Canary Islands, Spain.

⁹ Isaac Newton Group of Telescopes/NFRA, Apartado de Correos 321, E-38780 Santa Cruz de la Palma, Tenerife, Canary Islands, Spain.

¹⁰ Kitt Peak National Observatory.

¹¹ Space Research Organization of the Netherlands, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands.

¹² This material may be found at <http://www.ing.iac.es>. The La Palma web-page is not maintained by the Astrophysical Journal.

TABLE 1
LOG OF OBSERVATIONS OF GRB 970508

Date (UT)	Telescope	U	B	V	R_c	I_c
May 9.20	WIYN	...	...	...	21.25 ± 0.05	...
May 9.93	WHT PF	20.61 ± 0.25	...	21.05 ± 0.05	20.88 ± 0.05	20.49 ± 0.18
May 10.03	WHT PF	...	...	...	20.46 ± 0.05	...
May 10.98	WHT PF	19.75 ± 0.25	20.70 ± 0.08	20.19 ± 0.05	19.92 ± 0.05	19.61 ± 0.30
May 11.01	WHT PF	...	...	...	19.77 ± 0.07	...
May 12.03	WHT PF	19.97 ± 0.25	21.21 ± 0.08	20.71 ± 0.05	20.30 ± 0.07	19.89 ± 0.18
May 22.97	WHT AUX	...	...	...	22.04 ± 0.07	...
Jul 4.19	WHT AUX	...	...	...	23.95 ± 0.20	...
Aug 26.9	WHT PF	...	...	...	24.57 ± 0.07	...

9.99 UT of the Landolt (1992) fields PG 1047+003 and PG 1530+57. For V , R_c , and I_c , we find good agreement with the results of Sokolov et al. (1997). To include a B -band calibration and avoid small calibration differences with respect to Sokolov et al. (1997), we used the B , V , R_c , and I_c reference stars (1, 2, and 4 in Fig. 1 [Pl. L1]) as given by Sokolov et al. (1997) (their star 3 was close to saturation and therefore was not used). Stars 2, 5, 6, and 7 were used as secondary photometric standards for the U band (see Fig. 1). We have corrected for a U -band atmospheric extinction of 1.3 times the nominal extinction (as Carlsberg Automatic Meridian Circle V -band extinction measurements indicate).¹³

¹³ This material may also be found at <http://www.ing.iac.es>. The La Palma webpage is not maintained by the Astrophysical Journal.

3. R_c -BAND DIFFERENTIAL OPTICAL LIGHT CURVE

In Figure 2, we present the R_c -band optical light curve, where we have included results of differential photometry (relative to local reference stars; *filled symbols*) and calibrated photometry (*open symbols*). The differential magnitudes in Table 1 were determined with respect to stars 1, 2, and 4. The other differential data are from Sokolov et al. (1997; determined with respect to stars 1, 2, 3, and 4), Pedersen et al. (1998), Garcia et al. (1997), Schaefer et al. (1997), and Chevalier et al. (1997). The magnitudes in the last four data sets were determined with respect to star 4 only. In the absolute calibration of these differential data sets, we used the R_c magnitudes of these reference stars as given by Sokolov et al. (1997). Note that this involves a correction to the data of Pedersen et al. (1998), Schaefer et al. (1997), and Chevalier et al. (1997) by -0.21 mag for the difference by that amount in R_c for the reference star 4 used by these authors. The difference, in our data, in the R_c magnitudes of the OT, resulting from the use of stars 1, 2, and 4, or only star 4 as a reference star, has an rms of 0.027 mag. For data sets with a sufficiently large number of points and covering a time interval of at least 50 days on the power-law decay part of the light curve (i.e., those of Sokolov et al. 1997, Pedersen et al. 1998, and our data), we made a second-order correction by a magnitude calibration offset, determined from the weighted average offset with respect to the power-law decay part of the light curve. The corrections are 0.027 ± 0.025 , -0.020 ± 0.022 , and 0.082 ± 0.031 for our data (Table 1), Sokolov et al. (1997), and Pedersen et al. (1998), respectively. We have assumed a conservative minimum error in the differential magnitudes of 0.05 mag.

The R_c -band light curve shows a maximum between May 10.2 and 10.8 UT, 1.3–1.9 days after the gamma-ray burst. We fitted the rising and decaying parts of the light curve with power laws, $F_R \propto t^\alpha$. For the fit to the rising part, we use both the nondifferential photometry and the differential data (without the second-order correction), assuming a minimum error of 0.10 mag. For the fit to the decaying part, we only use the second-order-corrected data. The R_c -band light curve rises for $-0.1 < \log t < 0.20$ with exponent $\alpha = 3.0 \pm 0.4$ ($\chi_r^2 = 5.0/6$). After the maximum ($\log t > 0.27$), we find $\alpha = -1.141 \pm 0.014$ ($\chi_r^2 = 49/20$). Including in the fit the nondifferential data and the other differential data, i.e., without the second-order correction (assuming a minimum error of 0.10 mag), gives $\alpha = -1.132 \pm 0.015$ ($\chi_r^2 = 74.6/38$). Since a hint of flattening of the light curve was reported (Pedersen et al. 1998), we have also fitted a power law plus a constant, $F_R = F_{R0}t^\alpha + C$, to the decay part of the second-order-corrected differential R_c -band light curve. We find $\alpha = -1.191 \pm 0.024$;

FIG. 2.—*Top panel:* the R_c -band light curve of GRB 970508. For the differential light curve (*filled symbols*), the data have been used from Table 1 (*filled stars*), Sokolov et al. (1997; *filled circles*), Pedersen et al. (1998; *filled squares*), Garcia et al. (1997; *filled triangles*), Schaefer et al. (1997; *filled diamonds*), and Chevalier et al. (1997; *cross*). The open circles represent nondifferential data from Djorgovski et al. (1997), Castro-Tirado et al. (1998), Mignoli et al. (1997), Kelemen (1997), Fruchter et al. (1997), and Metzger et al. (1997c). The four open squares represent wide R filter data by Pedersen et al. (1998). The power-law fit to the second-order-corrected data with exponent $\alpha = -1.141 \pm 0.014$ is represented by the solid line. A fit to the second-order-corrected data of a power law plus a constant, $F_R = F_{R0}t^\alpha + C$, with exponent $\alpha = -1.191 \pm 0.024$ is indicated by the dashed line. The constant C corresponds to a magnitude $R_c = 26.09 \pm 0.36$. *Bottom panel:* the fit to the power-law decay subtracted from the second-order-corrected data of Table 1 (*filled stars*), Sokolov et al. (1997; *filled circles*), and Pedersen et al. (1998; *filled squares*).

the constant C corresponds to $R_c = 26.09 \pm 0.36$ ($\chi_r^2 = 43/19$; note that this corresponds to $R_c = 26.30 \pm 0.36$ in the calibration of Pedersen et al. 1998).

We also determined the optical fluence S of the OT (3000–10000 Å), taking for its spectral slope $\beta = -1$ or $-\frac{1}{3}$ (see § 4). We find $S = (1.20 \pm 0.07) \times 10^{-7}$ ergs cm $^{-2}$ ($\beta = -1$) or $S = (1.90 \pm 0.12) \times 10^{-7}$ ergs cm $^{-2}$ ($\beta = -\frac{1}{3}$) for the fluence collected until day 110 after the event. Extrapolating the power-law decay beyond day 110, we find a total optical fluence $S_\infty = (1.36 \pm 0.08) \times 10^{-7}$ ergs cm $^{-2}$ ($\beta = -1$) and $S_\infty = (2.16 \pm 0.14) \times 10^{-7}$ ergs cm $^{-2}$ ($\beta = -\frac{1}{3}$).

4. BROADBAND OPTICAL FLUX DISTRIBUTION

Between May 9.905 and 10.033 UT, the R_c -band flux increased by 0.137 ± 0.014 mag hr $^{-1}$. In estimating the spectral energy distribution, we corrected the May 9.9 UT observations for this brightening; i.e., we assumed that in all passbands the rate of brightening is the same and reduced the magnitudes to a single epoch (May 9.93 UT). The May 10.98 UT observations occurred at maximum light (see Fig. 2), so we have not applied any corrections. Corrections to the May 12 data were calculated using a power-law fit to the decay part of the R_c -band light curve (see § 3). The corrections are minor (<0.04 mag) and marginally (<0.02) affect the spectral slope.

We fitted our B , V , R_c , and I_c photometry with a power law, $F_\nu \propto \nu^\beta$, using the photometric calibration of Bessell (1979, Table IV). (We chose to exclude the U -band data to be able to compare our results directly with Sokolov et al. 1997. This exclusion does not affect the spectral slope significantly.) Before the fits were made, the data were corrected for interstellar extinction A_V . Using the *IRAS* database, we have determined the 100 μ m cirrus flux in the direction of the OT, $I_{100} < 0.08$ MJy sr $^{-1}$ (2σ), corresponding to $A_V < 0.01$ (Laureijs 1989). However, to compare our results with those of Djorgovski et al. (1997), we also used their value for the interstellar extinction ($A_V = 0.08$, corresponding to their $A_B = 0.11$). The effect of varying the interstellar extinction on the spectral slope is small; the maximum correction to the exponent β (with respect to $A_V = 0.08$) is -0.10 (for $A_V = 0$). We have also taken the B , V , R_c , and I_c measurements of Sokolov et al. (1997), and the near simultaneous U and R_c measurements of Castro-Tirado et al. (1998), and determined β , correcting for an extinction of $A_V = 0.08$. In Figure 3, we have plotted the spectral slopes as a function of time, including the results of Djorgovski et al. (1997) and Metzger et al. (1997b).

5. DISCUSSION

The differential R_c light curve shows that deviations from a smooth power-law decay are moderate (rms = 0.15 mag; bottom panel in Fig. 2). The magnitude $R_c = 26.09 \pm 0.36$ for a possible underlying galaxy is consistent with the limits derived by Sahu et al. (1997b) and Pian et al. (1998), i.e., $R_c > 25.5$. We note, however, that the introduction of a constant to the power-law fit has not improved the χ^2 substantially; we conclude that the evidence for a flattening of the light curve at late times is not yet convincing.

The optical fluence S_∞ (3000–10000 Å, $\beta = -1$; § 3) is about 5% of the BATSE 20–1000 keV and 20% of the WFC 2–26 keV GRB fluences. A similar comparison with the X-ray afterglow (Piro et al. 1997a; $S_X = 7.3 \times 10^{-7}$ ergs cm $^{-2}$, 2–10 keV, from an extrapolation of the X-ray light curve for $t >$

FIG. 3.—The spectral slope β as a function of time in days after the burst (we used $A_V = 0.08$; see § 4). The data are from this Letter (open stars), Sokolov et al. (1997; crosses), Djorgovski et al. (1997; filled circle), Metzger et al. (1997b; open circle), and Castro-Tirado et al. (1998; open squares). The maximum of the light curve occurred between day 1.3 and day 1.9.

27 s) shows that the optical afterglow fluence is $\sim 20\%$ of the X-ray afterglow fluence.

The optical spectrum of the OT becomes redder before reaching maximum light (Fig. 3); afterward, the spectral slope remains constant. We distinguish three phases of the light curve: phase I is the rising phase ($\alpha = 3.0 \pm 0.4$, $\beta = -0.33 \pm 0.17$), phase II is at maximum light ($\alpha \sim 0$, $\beta = -0.9 \pm 0.10$), and phase III is the decaying phase ($\alpha = -1.141 \pm 0.014$, $\beta = -1.11 \pm 0.06$). Wijers, Rees, & Mészáros (1997) give a relation between the spectral slope β and the temporal slope α for the simplest fireball remnant model (a forward blast wave with single Lorentz factor Γ ; their eq. [2]) and for a “beamed” fireball; i.e., Γ and the energy per unit solid angle E are functions of angle (their eq. [4]). For phase III, we find very good agreement with $\alpha = -1.141 \pm 0.014$, implying $\beta = -1.094 \pm 0.009$ for the “beamed” case (a marginal agreement with $\beta = -0.761 \pm 0.009$ for the simple case). Phases I and II are not in agreement with the simple and beamed fireball models that predict less steep or even inverted spectral slopes β . However, these early phases might be explained by a continuous distribution of Lorentz factors (Rees & Mészáros 1998). Lower Γ (redder) material takes longer to sweep up a significant amount of external matter, and hence its emission is delayed with respect to the higher Γ (bluer) material. The lower Γ material catches up gradually with the decelerated higher Γ material. Hence, the rise of the light curve and the evolution from blue to red can be explained with the building up of the emission from material with lower Γ , while the power-law decay (phase III) sets in when most of the material has been mixed to a single Γ .

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FIG. 1.—WHT prime focus $3\frac{1}{2} \times 3\frac{1}{2}$ R_c -band image of the field of GRB 970508. Bond's variable (OT) and the six stars used for calibration are indicated. Note that Sokolov's star 3 (our star 5) is not indicated since we did not use it as a secondary B , V , R_c , and I_c photometric standard. The U -band magnitudes of the four U -band comparison stars, stars 2, 5, 6, and 7, are 19.92 ± 0.25 , 17.61 ± 0.25 , 18.99 ± 0.25 , and 19.26 ± 0.25 , respectively.

GALAMA et al. (see 497, L14)