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THE RAPID DECAY OF THE OPTICAL EMISSION FROM GRB 980326 AND ITS POSSIBLE IMPLICATIONS

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ABSTRACT

We report the discovery of the optical counterpart to GRB 980326. Its rapid optical decay can be characterized by a power law with exponent -2.10 ± 0.13 and a constant underlying source at $R_c = 25.5 \pm 0.5$. Its optical colors 2.1 days after the burst imply a spectral slope of -0.66 ± 0.70. The γ-ray spectrum as observed with BATSE shows that it is among the 4% softest bursts ever recorded. We argue that the rapid optical decay may be a reason for the nondetection of some low-energy afterglows of GRBs.

Subject headings: gamma rays: bursts — gamma rays: observations — radiation mechanisms: nonthermal

1. INTRODUCTION

The redshift determinations for GRB 970508 (Metzger et al. 1997) and GRB 971214 (Kulkarni et al. 1998) have demonstrated that GRBs originate at cosmological distances and are therefore the most powerful photon sources in the Universe, with peak luminosities exceeding 10^{52} ergs s^{-1}, assuming isotropic emission.

Afterglow studies of GRB 970228 (Galama et al. 1997, 1998a), GRB 970508 (Galama et al. 1998b, 1998c, 1998d; Pedersen et al. 1998; Castro-Tirado et al. 1998a), and GRB 971214 (Halpern et al. 1998; Diercks et al. 1998) show a generally good agreement with fireball model predictions (Wijers, Rees, & Mészarós 1997; Sari, Piran, & Narayan 1998, hereafter SPN98).

There are, however, a few marked cases in which no X-ray or optical afterglow is seen, most notably GRB 970111 (optical: Castro-Tirado et al. 1997 and Gorosabel et al. 1998; X-rays, debated: Feroci et al. 1998), GRB 970828 (optical: Groot et al. 1998a) and GRB 980302 (X-rays). In the last case, *RXTE*/PCA scanning, starting only 1.1 hr after the burst, found no X-ray afterglow at a level greater than 1 mcrab. One possible explanation for the lack of optical counterparts is the extinction by large column densities of gas and dust, obscuring the GRB afterglows (Groot et al. 1998a; Halpern et al. 1998). This might indicate an origin in star-forming regions where large quantities of gas and dust are present (see, e.g., Paczyński 1998). However, this scenario does not explain the nondetection of an X-ray afterglow so readily.

GRB 980326 was detected (Celidonio et al. 1998) on March 26.888 UT with one of the Wide Field Cameras (WFCs; Jager et al. 1997) and the Gamma Ray Burst Monitor (GRBM; Frontera et al. 1997; Feroci et al. 1997) on board *BeppoSAX* (Piro, Scarsi, & Butler 1995), with *Ulysses* (Hurley et al. 1998) and with the Burst and Transient Source Experiment (BATSE; Briggs et al. 1998) on board the *Compton Gamma Ray Observatory*. Its best WFC position is R.A. = $08^{h}36^{m}26^{s}$, decl. = $-18^{\circ}53'.0$ (J2000), with an $8'$ (radius) accuracy. *RXTE*/PCA scanning 8.5 hr after the burst sets an upper limit of 1.6×10^{-12} ergs cm^{-2} s^{-1} on the 2–10 keV X-ray afterglow of GRB 980326 (Marshall & Takeshima 1998). Time-of-arrival analysis between the *Ulysses* spacecraft, *BeppoSAX*, and BATSE allows the construction of an Interplanetary Network (IPN) annulus that intersects the *BeppoSAX* WFC camera error box (Hurley et al. 1998). The combined WFC/IPN error box is shown in Figure 1.

In the BATSE energy range (25–1800 keV) the event lasted ~5 s, is resolved into three narrow peaks, with a peak flux of 8.8×10^{-7} ergs cm^{-2} s^{-1}, over a 1 s timescale. This places it at the knee of the log$N$-log$P$ distribution (Meegan et al. 1996). Its total 25–1800 keV fluence was 1.4×10^{-6} ergs cm^{-2}. The event averaged spectrum has a shape typical of GRBs (photon index $-3.1^{+0.25}_{-0.5}$), but its $E_{\rm peak}$, where the νF_ν spectrum peaks, is unusually low: $E_{\rm peak} = 47 \pm 5$ keV. Only 4% of the bursts in the sample of Mallozzi et al. (1998; over 1200 GRBs) have

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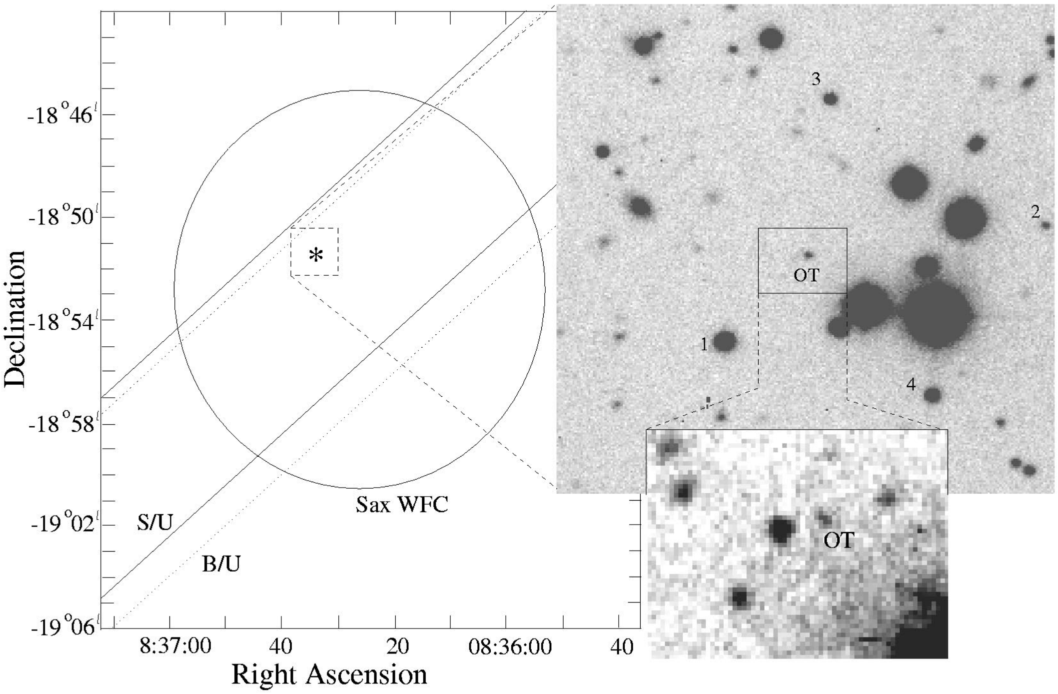

FIG. 1.—Combined *BeppoSAX* WFC and IPN arc error box for GRB 980326, an AAT March 27.4 UT, $1'.6 \times 1'.6$ R_C-band finding chart of the field of the optical transient and a small inset of the immediate surroundings of the OT, made from addition of the last three NTT nights. The solid IPN annulus is the *BeppoSAX*/*Ulysses* (S/U) annulus, the dotted annulus is the BATSE/*Ulysses* (B/U) annulus. Local comparison stars are indicated by no. 1–4.

smaller E_{peak}-values. However, Mallozzi et al. have also shown that there is a correlation between GRB intensity and spectral hardness (expressed in E_{peak}-values). For bursts with similar peak fluxes, the smallest E_{peak}-value there is ∼70 keV (R. S. Mallozzi 1997, private communication), which demonstrates the exceptional softness of the integrated spectrum of GRB 980326.

2. THE OPTICAL COUNTERPART

Optical Cousins R_C-band observations started at the Anglo-Australian Telescope (AAT) on March 27.40 UT, followed by observations at the 3.5 m New Technology Telescope (NTT) and the 1.54 m Danish telescope (1.5D) at ESO (Chile), the 4 m Victor Blanco telescope at CTIO (Chile), the Fred Lawrence Whipple 1.2 m (FLW 1.2 m; USA) telescope, the 1.5 m Bologna University (BO; Italy) telescope, and the 2.2 m Calar-Alto (CAHA 2.2 m; Spain) telescope (see Table 1). All observations were debiased and flat-fielded in the standard fashion. Table 2 shows the magnitude of the comparison stars in all photometric bands used. Note that star 2 (see Fig. 1) was not detected in the *B*-band calibration frames.

From a comparison of the first observations at the AAT and ESO/CTIO we discovered one clearly variable object (Groot et al. 1998b). Its location is R.A. = 08^{h}36^{m}34^s.28, decl. = $-18°51'23''.9$ (J2000) with an $0''.4$ accuracy. Figure 1 shows the region of the OT. Aperture photometry on the combined WFC/IPN error box for the first AAT and CTIO epoch found, apart from asteroid 1998 FO 126 at $R_C = 22.7$, no other object with a change in magnitude of more than 0.4 mag down to $R_C = 23$. Although the variability of sources at $R_C > 20$ is very poorly known, we conclude that the optical transient is the counterpart to GRB 980326, also considering the exhibited power-law decay.

Figure 2 shows the R_C-band light curve of the optical transient. It exhibits a temporal decay that, as applied in previous bursts, can be fitted with a power law and a constant source: $F_\nu \propto t^{-\alpha} + C$. The power-law exponent, $\alpha = 2.10 \pm 0.13$, is far higher than that of previous afterglows. The light curve exhibits a flattening, with a fitted constant source of 25.5 ± 0.5 (χ^2 for the fit is 10.2/9), such as observed for GRB 970508 (Pedersen et al. 1998; Garcia et al. 1998; Castro-Tirado et al. 1998b), which is possibly the signature of an underlying host galaxy. Grossan et al. (1998) reported an elongation in the NE-SW direction, which is also suggested by visual inspection of the NTT observations taken April 1.08 UT, but S/N levels are too low to draw any conclusion. Visual inspection of the observations reported by Djorgovski et al. (1998) displays an elongation in exactly the perpendicular direction (SE-NW), which may be an effect of fading of the optical transient. This would mean that it is not in the center of an underlying galaxy.

On the night of March 29.0 UT, broadband BVI_c measurements of the optical transient were made at the NTT (V and I_c) and at CTIO (B). From the fit to the light curve presented in Figure 2 we deduce an R_C-band value of 24.50 ± 0.10 at Mar 29.0 UT. The colors of the transient at this time were $B - R_C = 0.53 \pm 0.34$, $V - R_C > -0.25$, $R_C - I_c < 2.1$ (3 σ limits on V and I_c). The $B - R_C$-value implies an, uncertain, spectral power-law index, $F(\nu) \propto \nu^{-\beta}$, of $\beta = 0.66 \pm 0.70$. One has to realize though, that the underlying source might contribute significantly to the colors, depending on the difference between the afterglow and constant source spectrum.

3. CONSTRAINTS ON THE ELECTRON DISTRIBUTION

Afterglow observations of GRBs over the last year show that a relativistic blast wave, in which the highly relativistic electrons radiate via the synchrotron mechanism, provides a generally good description of the observed properties (Wijers et al. 1997; SPN98). Here we will discuss briefly the impli-

TABLE 1

LOG OF OBSERVATIONS OF GRB 980326, SUPPLEMENTED WITH PUBLISHED OBSERVATIONS OF THE KECK II AND KPNO 4 METER TELESCOPES

Date (UT)	Telescope	Integration Time (s)	Magnitude OT	Reference
Mar 27.31	Keck II		$R_C = 21.19 \pm 0.1$	GCN 33
Mar 27.401	AAT	240	$R_C = 21.98 \pm 0.16$	
Mar 27.437	AAT	240	$R_C = 22.18 \pm 0.16$	
Mar 27.84	BO 1.5 m	3600	$R_C > 21.85$	GCN 42
Mar 27.852	CAHA	3300	$R_C > 22.0$	
Mar 28.016	ESO NTT	1200	$R_C = 23.66 \pm 0.12$	
Mar 28.017	ESO 1.5Dan	2700	$R_C = 23.43 \pm 0.25$	
Mar 28.045	CTIO 4 m	600	$R_C = 23.50 \pm 0.12$	
Mar 28.120	FLW 1.2 m	3600	$R_C > 22.5$	
Mar 28.178	ESO NTT	1200	$R_C = 23.60 \pm 0.12$	
Mar 28.25	Keck II		$R_C = 23.69 \pm 0.1$	GCN 32
Mar 29.09	CTIO 4 m	3120	$B = 25.03 \pm 0.33$	
Mar 29.035	ESO NTT	1800	$I_c > 22.4$	
Mar 29.008	ESO NTT	1800	$V > 24.2$	
Mar 29.424	AAT	480	$R_C > 23.0$	
Mar 30.078	ESO NTT	5400	$R_C = 24.88^{+0.32}_{-0.26}$	
Mar 30.2	Keck II		$R_C = 25.03 \pm 0.15$	GCN 35
Mar 31.082	ESO NTT	5400	$R_C = 25.20^{+0.23}_{-0.20}$	
Apr. 1.080	ESO NTT	5400	$R_C > 24.9$	
Apr. 7.15	KPNO 4 m	3300	$R_C > 24.4$	
Apr. 17.3	Keck II		$R_C = 25.5 \pm 0.5$	GCN 57

cations of the power-law decay exponent α and the optical spectral slope β for a number of different blast wave models. For an extensive discussion on blast wave models and their application to GRB afterglows, we refer the reader to Wijers et al. (1997), SPN98, and Galama et al. (1998c).

All models have that the flux $F(\nu,t) \propto t^{-\alpha}\nu^{-\beta}$ for a range of frequencies and times that contain no spectral breaks. In each model or spectral state of a model α and β are functions only of p, the power-law exponent of the electron Lorentz factor (γ_e) distribution, $N(\gamma_e) \propto \gamma_e^{-p}$. The measurement of either one of α or β therefore fixes p, and predicts the other one.

Given the poor constraint on the spectral slope, we cannot uniquely fit GRB 980326, but we will examine whether its rapid decay requires special circumstances. First, we assume that both the peak frequency ν_m and the cooling frequency ν_c (see SPN98 for their definitions) have passed the optical passband at 0.5 days. In this case, $p = (4\alpha + 2)/3 = 3.5 \pm 0.1$, and $\beta = p/2 = 1.75 \pm 0.06$. The second possibility is one in which ν_m has already passed the optical at 0.5 days, but ν_c not yet at 4.2 days. In this state $p = (4\alpha + 3)/3 = 3.8 \pm 0.1$, and $\beta = -(1 - p)/2 = 1.4 \pm 0.06$. Although the latter case agrees slightly better with the measured $B - R_C$ spectral slope, we are hesitant to draw any conclusion from this, considering the uncertainty of the spectral slope. Both, however, imply a much steeper electron spectrum for this burst than the value $p = 2.2$ derived for GRB 970508 (Galama et al. 1998c, 1998d). In case the blast wave is jetlike, the inferred electron spectrum will only be different if the opening angle, θ, of the jet is less than the inverse of the opening angle, here less than 7°, in which case for slowly cooling electrons $p = \alpha = 2.1$, and for rapidly cooling electrons $p = \alpha - 1 = 1.1$ (Rhoads 1998). In both cases $\beta = 0.55 \pm 0.05$, consistent with the optical color. Values of p less than 2 are often considered implausible, because they imply a very efficient acceleration mechanism in which the most energetic electrons carry the bulk of the energy.

TABLE 2

THE MAGNITUDES OF THE FOUR COMPARISON STARS USED

Star Number	B	V	R_C	I_c
1	20.05 ± 0.10	19.17 ± 0.07	18.51 ± 0.03	18.11 ± 0.02
2	...	23.04 ± 0.15	21.85 ± 0.10	20.74 ± 0.05
3	21.08 ± 0.10	20.76 ± 0.05	20.40 ± 0.05	20.00 ± 0.02
4	20.73 ± 0.10	20.22 ± 0.05	19.78 ± 0.03	19.53 ± 0.02

NOTES.—Photometric calibration of our observations was performed using Landolt 1992 standard fields SA98 and Rubin 149 (R_C band, taken at the AAT at March 27.4 UT), and PG1047+003 (B, V and I_c band, taken at ESO at March 30.05 UT).

4. THE MAXIMUM VALUE OF p

What is the maximum value of p that can be reached in shock acceleration? In nonrelativistic strong shocks it is generally accepted that $p \sim 2$ (Bell 1978; Blandford & Ostriker 1978). In ultrarelativistic shocks, however, the situation is not so clear (Quenby & Lieu 1989). Recent calculations show that in this case p will be between 3.2 and 3.8, depending on the morphology of the magnetic field (Achterberg & Gallant 1998). This is, however, when the electrons do not radiate an appre-

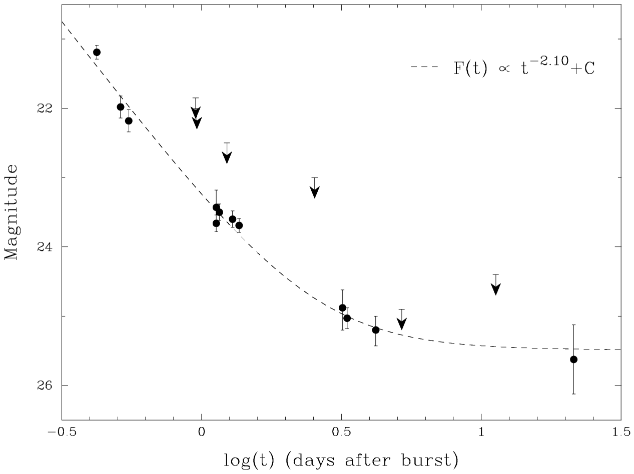

FIG. 2.—R_C-band light curve of GRB 980326. All errors are 1 σ, all upper limits are 3 σ. The dashed line indicates the power-law decay and constant source fit (see § 2).

ciable part of their energy during shock acceleration. If the electrons do radiate significantly, as is suggested by GRB 970508 (Galama et al. 1998c, 1998d; SPN98), the electron spectrum will steepen and the distribution of electrons will no longer be a pure power law. In a power-law model fit, measured values exceeding $p \sim 3.8$ are therefore expected, and as a consequence, power-law decays of afterglows that are even more rapid than the $\alpha = 2.10$ found here are entirely possible.

5. EXPLANATIONS FOR NONDETECTIONS: RAPID DECAYS AND GALACTIC HALOS

The optical behavior of bursts like GRB 970828 (Groot et al. 1998a) and GRB 971214 (Halpern et al. 1998) can be explained by extinction caused by gas and dust between the observer and the origin of the GRB source. However, extinction will fail to explain the nonexistence of an X-ray afterglow above 4–5 keV, since at these energies extinction is negligible. The fact that all *BeppoSAX* NFI follow-ups have detected an X-ray afterglow (with the possible exception of GRB 970111; Feroci et al. 1998) and that only two *RXTE*/PCA scannings (for GRB 970616 and GRB 970828) have produced X-ray afterglows, makes the question what causes of this difference to arise.

Suppose we have an X-ray afterglow that decays as a power law with exponent α. What is the X-ray afterglow flux needed shortly (~1 minute) after the burst, as a function of α, if we want to detect the afterglow at a level of ~1 mcrab after a few hours? The X-ray flux after 1 minute can be estimated by the X-ray emission detected in the burst itself, since this X-ray emission will be a mixture of the X-ray tail of the GRB and the start of the X-ray afterglow. We can therefore derive an estimate of the upper limit to the X-ray afterglow level after a few hours from the prompt X-ray emission.

Figure 3 shows the flux needed after 1 minute for a detection after 1, 2, and 5 hr at a level of 1 mcrab as a function of decay rate α. For bursts that have detected X-ray or optical afterglows we have also plotted in Figure 3 the observed total X-ray fluxes during the bursts versus the X-ray power-law decay index α. (For GRB 980326 we used the optical α, since no X-ray afterglow decay index is known.) Because of the mixture explained above, these points actually comprise a set of upper limits for the flux in the X-ray afterglow after one minute. It is not only clear from Figure 3 that most of the bursts that have been found to exhibit an X-ray afterglow would have been missed by an *RXTE*/PCA scan after 2–5 hr, but also that this is particularly the case for bursts with high values of α. A rapid decay is therefore a viable explanation for the nondetection of bursts, even as bright as GRB 980203, by the current *RXTE*/PCA follow-up. It has to be noted that the scanning of the *RXTE*/PCA is often performed over no more than the 1.5–2 σ BATSE error boxes, and there exists therefore a 5%–14% chance of not scanning the GRB.

For bursts that show neither X-ray nor optical afterglows, a different explanation may be found in the fact that all five detected optical afterglows are associated with galaxies. In the merging neutron-star scenario, a substantial fraction of bursts would occur in a galactic halo, where the average density of the interstellar medium is ~1000 times less than in a disk. Since the afterglow peak flux, F_m, depends on the square root of the density of the ambient medium, this would mean a reduction of the afterglow peak flux by several magnitudes with respect to bursts that go off in higher density regions (Mészáros & Rees 1997). Since GRBs are detected by their prompt γ-ray emission, probably produced by internal shocks (Mészáros & Rees 1997), this would be independent of the density of the ambient medium.

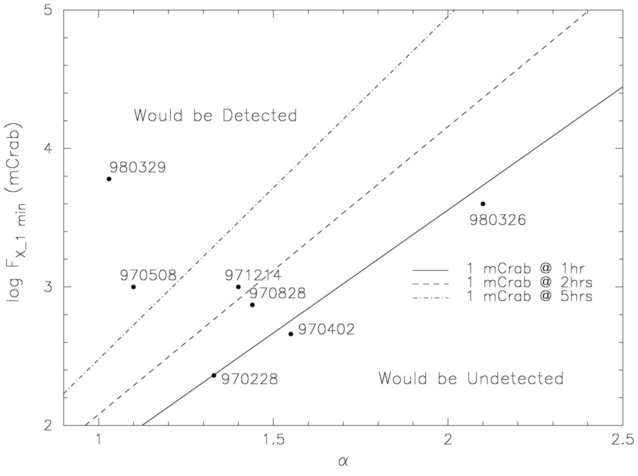

FIG. 3.—X-ray flux needed after 1 minute to detect a GRB after 1 (*solid line*) or 2 (*dashed line*) and 5 (*dashed-dotted line*) hr at a level of 1 mcrab as a function of temporal decay power-law index α. Indicated for several bursts with measured α is the *total* X-ray flux during the GRB event. References: GRB 970228, Costa et al. (1997); GRB 970402, Nicastro (1998); GRB 970508, Galama et al. (1998a), Sokolov et al. (1998); GRB 970828, Yoshida et al. (1998); GRB 971214, Halpern et al. (1998), Diercks et al. (1998); GRB 980326, this Letter; GRB 980329, in 't Zand et al. (1998).

6. CONCLUSIONS

We have detected the optical counterpart to GRB 980326. Its temporal decay is well represented by a power law with index −2.10, faster than for any previously found GRB afterglow, and a constant contribution at $R_C = 25.5 \pm 0.5$, which is most likely caused by an underlying galaxy. Fireball models can give an adequate description of this rapid power-law decay of GRB 980326, although its limited optical spectral information makes it hard to distinguish between different models. This emphasizes the need for multicolor photometry, even when the optical counterpart has not yet been found.

A rapid temporal decay may be a reason for the nondetection of low-energy afterglows of bursts that had X-ray and optical follow-ups. The occurrence of GRBs in galactic halos, in the merging neutron star scenario, may be an alternative explanation for the nondetection of low-energy afterglows. To establish the viability of these explanations for the nondetection of low-energy afterglows, it is of vital importance that more GRB afterglows are found and this is only possible when low-energy follow-up begins as soon as possible (<1 hr) after the initial GRB event.

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