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 ±0.5. Its optical colours 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

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argue that the rapid optical decay may be a reason for the non-detection of some low-energy afterglows of GRBs.

Subject headings: Gamma-rays bursts—gamma-rays:observations—radiation mechanisms:non-thermal

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} erg/s, assuming isotropic emission. Afterglow studies of GRB 970228 (Galama et al., 1997, 1998a), GRB 970508 (Galama et al., 1998b, c, d; 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 and Mészarós, 1997; Sari, Piran and Narayan, 1998, hereafter SPN98).

There are, however, a few marked cases where no X-ray or optical afterglow is seen, most notably GRB 970111 (optical:Castro-Tirado et al., 1997; 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 hours after the burst, found no X-ray afterglow at a level >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 (e.g. Paczyński, 1998). However, this scenario does not so readily explain the non-detection of an X-ray afterglow.

GRB 980326 was detected (Celidonio et al., 1998) on Mar. 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 and 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 RA= $08^h36^m26^s$, Decl = $-18°53'.0$ (J2000), with an $8'$ (radius) accuracy. RXTE/PCA scanning 8.5 hours after the burst sets an upper limit of 1.6×10^{-12} erg cm^{-2} s^{-1} on the 2–10 keV X-ray afterglow of GRB 980326 (Marshall and Takeshima 1998). Time-of-arrival analysis between the Ulysses spacecraft, BeppoSAX and BATSE, allows the construction of an Interplanetary Network (IPN) annulus which intersects the

BeppoSAX WFC camera error box (Hurley et al., 1998). The combined WFC/IPN error box is shown in Fig. 1.

In the BATSE energy range (25–1800 keV) the event lasted $\sim$ 5s, is resolved into three narrow peaks, with a peak flux of 8.8×10^{-7} ergs cm^{-2} s^{-1}, over a 1s 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 smaller $E_{\rm peak}$ values. However, Mallozzi et al. have also shown that there is a correlation between GRB intensity and spectral hardness (expressed in $E_{\rm peak}$ values). For bursts with similar peak fluxes, the smallest $E_{\rm peak}$ value there is $\sim$ 70 keV (Mallozzi, private communication), which demonstrates the exceptional softness of the integrated spectrum of GRB 980326.

2. The optical counterpart

Optical Cousins $R_{\rm c}$-band observations started at the Anglo-Australian Telescope (AAT) on Mar. 27.40 UT, followed by observations at the 3.5m New Technology Telescope (NTT) and the 1.54m Danish telescope (1.5D) at ESO (Chile), the 4m Victor Blanco telescope at CTIO (Chile), the Fred Lawrence Whipple 1.2m (FLW 1.2m; USA) telescope, the 1.5m Bologna University (BO; Italy) telescope and the 2.2m Calar-Alto (CAHA 2.2m; Spain) telescope (see Table 1). All observations were debiased and flatfielded 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 RA=$08^{\rm h}36^{\rm m}34\overset{\rm s}{.}28$, Dec = $-18^\circ51'23\overset{''}{.}9$ (J2000) with an $0\overset{''}{.}4$ accuracy. Fig. 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 $R_{\rm c}$=22.7, no other object with a change in magnitude >0.4 mag down to $R_{\rm c}$=23. Although the variability of sources at $R_{\rm c} > 20$ 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 $R_{\rm c}$-band light curve of the optical transient. It exhibits a temporal decay which, 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, α = 2.10$\pm$0.13, is by 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 Mar. 29.0 UT broadband $BVI_{\rm c}$ measurements of the optical transient were made at the NTT (V and $I_{\rm c}$) and at CTIO (B). From the fit to the light curve presented in Fig. 2 we deduce an $R_{\rm c}$-band value of 24.50 ± 0.10 at Mar 29.0 UT. The colours of the transient at this time were $B - R_{\rm c} = 0.53 \pm 0.34$, $V - R_{\rm c} > -0.25$, $R_{\rm c} - I_{\rm c} < 2.1$ (3σ limits on V and $I_{\rm c}$). The $B - R_{\rm c}$ value implies an, uncertain, spectral power law index, $F(\nu) \propto \nu^{-\beta}$, of $\beta = 0.66 \pm 0.70$. One has to realise though, that the underlying source might contribute significantly to the colours, 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, Rees and Meszárós,1997; SPN98). Here we will discuss briefly the implications 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, Rees and Meszárós (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 which 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 $\nu_{\rm m}$ and the cooling frequency $\nu_{\rm c}$ (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 β=$p/2$ = 1.75 $\pm$0.06. The second possibility is when $\nu_{\rm m}$ has already passed the optical at 0.5 days, but $\nu_{\rm c}$ 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 $B - R_{\rm c}$ spectral slope, we are hesistant 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, d). In case the blast wave is jet-like, 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 $< 7°$, 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 colour. 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.

4. The maximum value of p

What is the maximum value of p that can be reached in shock acceleration? In non-relativistic strong shocks it is generally accepted that $p \sim$2 (Bell, 1978; Blandford and Ostriker, 1978). In ultra-relativistic shocks however, the situation is not so clear (Quenby and 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 and Gallant, 1998). This is, however, when the electrons do not radiate an appreciable part of their energy during shock acceleration. If the electrons do radiate significantly, as is suggested GRB 970508 (Galama et al., 1998c,d; 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 α=2.10 found here are entirely possible.

5. Explanations for non-detections: rapid decays and galactic halos

The optical behaviour of bursts like GRB 970828 (Groot et al., 1998a) and GRB 971214 (Halpern et al., 1998) can be explained by extinction due to gas and dust between the observer and the origin of the GRB source. However extinction will fail to explain the non-existence 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 arise what the cause of this difference is.

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 ($\sim$ 1 minute) after the burst, as a function of α, if we want to detect the afterglow at a level of $\sim$ 1mCrab 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 hours 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 Fig. 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 Fig. 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 hours, 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 non-detection 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 1.5–2σ BATSE errorboxes, 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 $\sim$1000 times less than in a disk. Since the afterglow peak flux, $F_{\rm m}$, 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 and Rees, 1997). Since GRBs are detected by their prompt γ-ray emission, probably produced by internal shocks (Mészáros and Rees, 1997), this would be independent of the density of the ambient medium.

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 multi-colour photometry, even when the optical counterpart has not yet been found.

A rapid temporal decay may be a reason for the non-detection 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 non-detection of low-energy afterglows. To establish the viability of these explanations for the non-detection 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 (<1hr) after the initial GRB event.

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Fig. 1.— The combined BeppoSAX WFC and IPN arc error box for GRB 980326, an AAT Mar. 27.4 UT, 1'.6×1'.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.

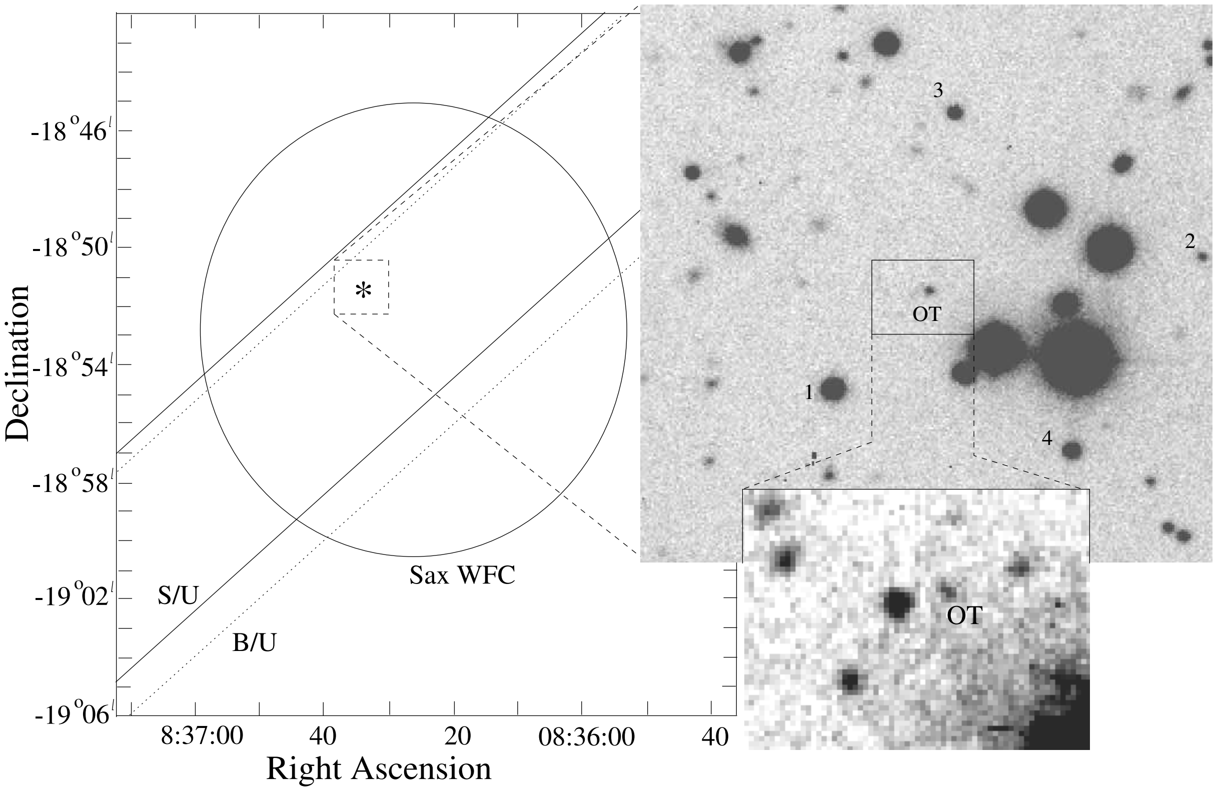

Fig. 2.— R_c-band light curve of GRB 980326. All errors are 1σ, all upper limits are 3σ. The dashed line indicates the power law decay and constant source fit (see Sect. 2).

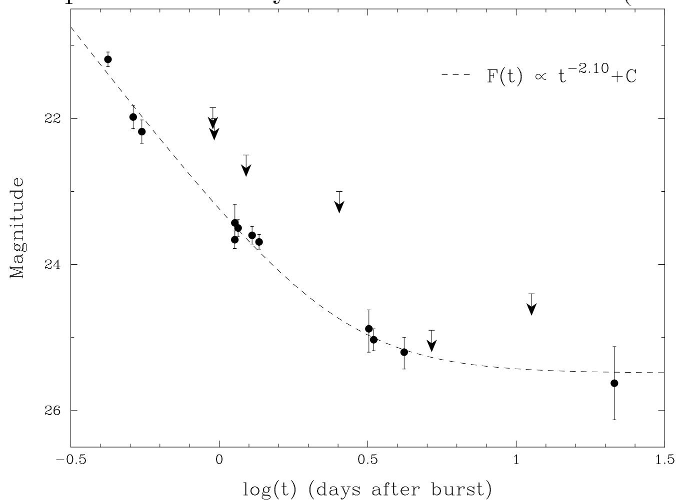

Fig. 3.— The X-ray flux needed after 1 minute to detect a GRB after 1 (solid line) or 2 (dashed line) and 5 (dashed-dotted line) hrs at a level of 1 mCrab as a function of temporal decay power law index α. Indicated for several bursts with measured α is the *total* X-ray flux during the GRB event. References: GRB 970228 Costa et al., 1997; GRB 970402 Nicastro et al., 1997; 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 paper; GRB 980329 In 't Zand et al., 1998.

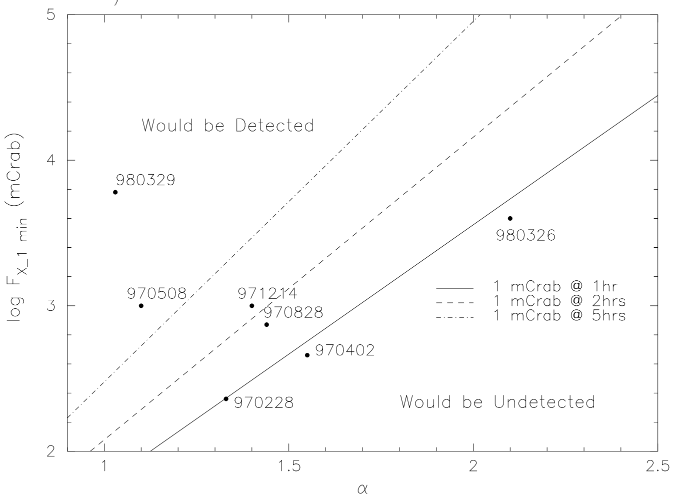

Table 1: Log of observations of GRB 980326, supplemented with published observations of the Keck II and KPNO 4-m telescopes.

Date (UT)	Telescope	Integration time (s)	Magnitude OT	Reference
Mar. 27.31	Keck II		R_c=21.19 ± 0.1	GCN #33
Mar. 27.401	AAT	240	R_c=21.98 ± 0.16	
Mar. 27.437	AAT	240	R_c=22.18 ± 0.16	
Mar. 27.84	BO 1.5m	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 ± 0.12	
Mar. 28.017	ESO 1.5Dan	2700	R_c=23.43 ± 0.25	
Mar. 28.045	CTIO 4m	600	R_c=23.50 ± 0.12	
Mar. 28.120	FLW 1.2m	3600	R_c >22.5	
Mar. 28.178	ESO NTT	1200	R_c=23.60 ± 0.12	
Mar. 28.25	Keck II		R_c=23.69 ± 0.1	GCN # 32
Mar. 29.09	CTIO 4m	3120	B=25.03±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 ± 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 4m	3300	R_c >24.4	
Apr. 17.3	Keck II		R_c=25.5±0.5	GCN #57

Table 2: The magnitudes of the four comparison stars used[a]

Star no.	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

[a]Photometric calibration of our observations was performed using Landolt (1992) standard fields SA98 and Rubin 149 (R_c-band, taken at the AAT at Mar. 27.4 UT), and PG1047+003 (B, V and I_c-band, taken at ESO at Mar. 30.05 UT).