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

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Received 1998 April 24; accepted 1998 May 28; published 1998 July 9

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 $-2.10 \pm 0.13$ and a constant underlying source at $R_e = 25.5 \pm 0.5$. Its optical colors 2.1 days after the burst imply a spectral slope of $-0.66 \pm 0.70$. The $\gamma$-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 $10^{53}$ erg s$^{-1}$, assuming isotropic emission.

Afterglow studies of GRB 970228 (Galama et al. 1997, 1999), 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, 1998. The American Astronomical Society. All rights reserved. Printed in U.S.A.)
smaller $E_{\text{peak}}$-values. However, Mallozzi et al. have also shown that there is a correlation between GRB intensity and spectral hardness (expressed in $E_{\text{peak}}$-values). For bursts with similar peak fluxes, the smallest $E_{\text{peak}}$-value there is $\sim 70$ 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$^\circ$36$^\prime$34$''$.28, decl. = $-18^\circ$51$'$23$''$.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: $F(R) \propto R^{-\alpha} + C$. 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 (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 $24.50 \pm 0.10$ 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 $\sigma$ 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-
cations of the power-law decay exponent $\alpha$ and the optical spectral slope $\beta$ 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), SPN 98, and Galama et al. (1998c).

All models have that the flux $F(\nu,t) \propto \nu^{-\alpha-\beta}$ for a range of frequencies and times that contain no spectral breaks. In each model or spectral state of a model $\alpha$ and $\beta$ are functions only of $\nu$, the power-law exponent of the electron Lorentz factor ($\gamma_e$) distribution, $N(\gamma_e) \propto \gamma_e^{-\gamma}$. The measurement of either one of $\alpha$ or $\beta$ therefore fixes $\nu$, 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 $\nu_p$ and the cooling frequency $\nu_c$ (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 $\nu_p$ has already passed the optical at 0.5 days, but $\nu_c$ 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, $\theta$, of the jet is less than the inverse of the opening angle, here less than $7^\circ$, 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.

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 $\sigma$, all upper limits are 3 $\sigma$. The dashed line indicates the power-law decay and constant source fit (see § 2).](Image 324x73 to 561x250)

### TABLE 1

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

### TABLE 2

| Star Number | $B$ | $V$ | $R_C$ | $I_c$ |
|-------------|-----|-----|------|------|
| 1           | 20.05 $\pm$ 0.10 | 19.17 $\pm$ 0.07 | 18.51 $\pm$ 0.03 | 18.11 $\pm$ 0.02 |
| 2           | 23.04 $\pm$ 0.15 | 21.85 $\pm$ 0.10 | 20.74 $\pm$ 0.05 |  |
| 3           | 21.08 $\pm$ 0.10 | 20.76 $\pm$ 0.05 | 20.40 $\pm$ 0.05 |  |
| 4           | 20.73 $\pm$ 0.10 | 20.22 $\pm$ 0.05 | 19.78 $\pm$ 0.03 | 19.53 $\pm$ 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).
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 $p \approx 3.8$ 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 scans (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 $\alpha$. What is the X-ray afterglow flux needed shortly ($\sim 1$ minute) after the burst, as a function of $\alpha$, if we want to detect the afterglow at a level of $\sim 1$ 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 $\alpha$. 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 $\alpha$. (For GRB 980326 we used the optical $\alpha$, 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 $\alpha$. 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 $\sigma$ 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 $\sim$1000 times less than in a disk. Since the afterglow peak flux, $F_{\nu}$, 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 $\gamma$-ray emission, probably produced by internal shocks (Mészáros & 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 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.

P. J. G. wishes to thank Bram Achterberg for useful discussions. T. J. G. is supported through a grant from NFR under contract 781.76.011. R. A. M. J. is supported by a Royal Society URF grant. C. K. acknowledges support from NASA grant NAG 5-2560. J. G. is supported by BMBF/DFL under contract FKZ 50 QQ 9602.
REFERENCES

Achterberg, A., & Gallant, Y. 1998, MNRAS, in preparation
Bell, A. R. 1978, MNRAS, 182, 147
Blandford, R. P., & Ostriker, J. P. 1978, ApJ, 221, L29
Briggs, M., et al. 1998, IAU Circ. 6856
Castro-Tirado, A., et al. 1997, IAU Circ. 6598
———. 1998a, Science, 279, 1011
———. 1998b, IAU Circ. 6848
Celionio, G., et al. 1998, IAU Circ. 6851
Costa, E., et al. 1997, Nature, 387, 783
Diercks, A., et al. 1998, ApJ, in press (astro-ph/9803305)
Djorgovski, G., et al. 1998, GCN Circ. 41 (http://gcn.gsfc.nasa.gov/gcn/gcn3/041.gcn3)
Feroci, M., et al. 1997, Proc. SPIE, 3114, 186
———. 1998, A&A, 332, L29
Frontera, F., et al. 1997, A&AS, 122, 357
Galama, T. J., et al. 1997, Nature 387, 479
———. 1998a, in AIP Conf. Proc. 428, Fourth Huntsville Symp. on Gamma-Ray Bursts, ed. C. A. Meegan, T. M. Koshut, & R. D. Preece (New York: AIP), 478
———. 1998b, ApJ, 497, L13
———. 1998c, ApJ, 500, L101
———. 1998d, ApJ, 500, L97
Garcia, M., et al. 1998, ApJ, 500, L105
Gorosabel, J., et al. 1998, A&A, submitted
Groot, P. J., et al. 1998a, ApJ, 493, L27
———. 1998b, IAU Circ. 6852
Grossan, B., et al. 1998, GCN Circ. 35 (http://gcn.gsfc.nasa.gov/gcn/gcn3/035.gcn3)
Halpern, J. P., et al. 1998, Nature, 393, 41
Hurley, K., et al. 1998, GCN Circ. 53 (http://gcn.gsfc.nasa.gov/gcn/gcn3/053.gcn3)
in ’t Zand, J. J. M., et al. 1998, in preparation
Jager, R., et al. 1997, A&AS, 125, 557
Kulkarni, S. R., et al. 1998, Nature, 393, 35
Landolt, A. U. 1992, AJ, 104, 340
Mallozzi, R. S., Pendleton, G. N., Paciesas, W. S., Preece R. D., & Briggs, M. S. 1998, in AIP Conf. Proc. 428, Fourth Huntsville Symp. on Gamma-Ray Bursts, ed. C. A. Meegan, T. M. Koshut, & R. D. Preece (New York: AIP), 273
Marshall, F., & Takeshima, T. 1998, GCN Circ. 58 (http://gcn.gsfc.nasa.gov/gcn/gcn3/058.gcn3)
Meegan, C. A., et al. 1996, ApJS, 106, 65
Mészáros, P., & Rees, M. J. 1997, ApJ, 476, 232
Metzger, M. R., et al. 1997, Nature, 387, 879
Nicastro, L. 1998, A&A, accepted
Paczynski, B. 1998, ApJ, 494, L45
Pedersen, H., et al. 1998, ApJ, 496, 311
Piro, L., Scarsi, L., & Butler, R. C. 1995, Proc. SPIE, 2517, 169
Quenby, J. J., & Lieu, R. 1989, Nature, 342, 654
Rhoads, J. E. 1998, in AIP Conf. Proc. 428, Fourth Huntsville Symp. on Gamma-Ray Bursts, ed. C. A. Meegan, T. M. Koshut, & R. D. Preece (New York: AIP), 699
Sari, R., Piran, T., & Narayan, R. 1998, ApJ, 497, L17
Sokolov, V. V., et al. 1998, A&A, 334, 117
Wijers, R. A. M., Rees, M. J., & Mészáros, P. 1997, MNRAS, 288, L51
Yoshida, A., et al. 1998, in AIP Conf. Proc. 428, Fourth Huntsville Symp. on Gamma-Ray Bursts, ed. C. A. Meegan, T. M. Koshut, & R. D. Preece (New York: AIP), 441