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POWER-LAW DECAYS IN THE OPTICAL COUNTERPARTS OF GRB 970228 AND GRB 970508

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ABSTRACT

We report on R_C- and K-band observations of the optical counterpart to GRB 970508 with the Fred Lawrence Whipple Observatory (FLWO) 1.2 m telescope. Eleven R_C-band observations were obtained on 1997 May 12, and three on May 14. The counterpart clearly faded between the two nights. On May 12 there was no evidence for variability (<9%) on 10–70 minute timescales based on 11 R_c-band observations. On May 19 a 1 hr observation set a limit on the K magnitude of $K > 18.6$. Comparison of these data points with those obtained by other authors shows that the decay of the optical counterpart can be well fitted by a power law of the form $f \sim t^{-\alpha}$, where $\alpha = 1.22 \pm 0.03$ with occasional fluctuations superposed. We note that the decay of the optical counterpart to another burst, GRB 970228, can also be well fitted with a power law with exponent $\alpha = 1.0^{+0.2}_{-0.5}$ with occasional fluctuations superposed. These two decay light curves are remarkably similar in form to that predicted by cosmic-fireball models.

Subject heading: gamma rays: bursts

1. INTRODUCTION

Since their discovery nearly 30 years ago (Klebesabel, Strong, & Olson 1973), the nature of gamma-ray bursts (GRBs) has been one of the outstanding problems in astrophysics. Bursts with fluxes sufficient to be detected by CGRO/BATSE are detected approximately once per day, and these bursts are isotropically distributed on the sky (Meegan et al. 1992). The observed fluxes of GRBs indicate that this isotropic distribution is also limited in extent, a fact that has been used to argue that GRBs are at cosmological distances (Meegan et al. 1992). However, because of the previous lack of counterparts at other wavelengths, the distances to GRBs have been uncertain by ~5 orders of magnitude, leading to ~10 orders of magnitude uncertainty in their luminosity. Progress in understanding GRBs has been hampered by this uncertainty.

The precise locations determined with the Wide Field Camera (WFC) on board the recently launched Italian-Dutch *BeppoSAX* observatory have allowed the discovery of the first optical counterparts to GRBs, for GRB 970228 (Groot et al. 1997b; Van Paradijs et al. 1997), GRB 970508 (Bond 1997), GRB 971214 (Halpern et al. 1997), and GRB 980326 (Groot et al. 1998). Three of these appear to be at cosmological distances: GRB 970228 and GRB 980326 are surrounded by nebulosity that is most likely a galaxy (Van Paradijs et al. 1997; Grossan et al. 1998), and GRB 970508 shows optical absorption lines at redshifts of $z = 0.767$ and $z = 0.835$ (Metzger et al. 1997b). The light curves of the optical counterparts to GRBs give hints as to the underlying physics of the GRB. We report below a modest set of optical and IR photometric observations of the optical counterpart to GRB 970508.

2. OBSERVATIONS

Discovery of the optical counterpart to GRB 970508 was first announced by Bond (1997) shortly after *BeppoSAX* WFC observations yielded an arcminute location for an X-ray afterglow to the GRB (Costa et al. 1997). The counterpart rose to a maximum $R_C = 19.70 \pm 0.03$ on May 10.77 UT (Sokolov et al. 1997), after which it faded. Our Cousins R-band (R_C) observations on May 12.2 UT and 14.2 UT were made during the decay phase, approximately 3.3 and 5.3 days after the detection of the GRB. The results in this Letter supersede that reported for the May 12 data in IAU Circ. 6661.

The observations were made with the FLWO 1.2 m telescope at Mount Hopkins, Arizona. We utilized a 2048 × 2048 pixel CCD camera with 0".32 pixels and a standard R_C-band filter (the "Andy-Cam"). On May 12 conditions were not photometric and the seeing varied from 2" to 3"; on May 14 conditions were better but still not photometric.

A journal of the observations and magnitudes is shown in Table 1. After bias subtracting and flat-fielding, the magnitudes were derived with DAOPHOT. Because conditions were not photometric, we have set our magnitude scale such that the nightly mean magnitude measured for the star 13" north and 4" west of the GRB counterpart (star A in Table 1) is $R_C = 19.49$, as was determined by Sokolov et al. (1997). The fluctuations in the magnitude of star A as measured in each individual exposure reflect both statistical variations and variable observing conditions. Included in Table 1 are the magnitudes of a star with magnitude similar to the GRB, but presumed to be nonvariable (star B in Table 1, 67" north and 63" west of the GRB counterpart). Exposure times were 5 minutes for the first 12 images and 20 minutes for the last two images. Dates are heliocentric Julian Day at midexposure. The mean and standard deviation (σ) for each night have been computed directly from the tabulated magnitudes.

The average magnitudes and midexposure times are $R_C = 20.23 \pm 0.02$ and $R_C = 21.03 \pm 0.07$, on JD 2,450,580.703 and JD 2,450,582.667, respectively. These quoted errors are $= \sigma/N^{1/2}$, and represent the statistical (internal) errors only.

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TABLE 1
JOURNAL OF FLWO 1.2 METER CCD OBSERVATIONS

Julian Day	GRB	B	A
(May 12.2 UT)			
2,450,580.6764	20.18	20.08	19.44
2,450,580.6805	20.30	20.27	19.48
2,450,580.6851	20.34	20.30	19.43
2,450,580.6953	20.27	20.20	19.43
2,450,580.6993	20.23	20.05	19.57
2,450,580.7032	20.17	20.15	19.57
2,450,580.7070	20.12	20.28	19.45
2,450,580.7109	20.22	20.16	19.46
2,450,580.7148	20.23	20.13	19.59
2,450,580.7198	20.23	20.30	19.41
2,450,580.7237	20.25	20.12	19.56
Mean	20.23	20.18	19.49
σ	00.06	00.09	00.07
(May 14.2 UT)			
2,450,582.6515	21.16	20.28	19.53
2,450,582.6655	20.98	20.41	19.48
2,450,582.6827	20.94	20.34	19.48
Mean	21.03	20.34	19.49
σ	00.12	00.07	00.03

On May 19.2 UT, approximately 10.3 days after the GRB detection, we observed the field of GRB 970508 for approximately 1 hr (from HJD = 2,450,587.7349 to 2,450,587.7673) with the FLWO 1.2 m telescope and the Smithsonian Astrophysical Observatory infrared camera STELIRCAM. The camera uses an InSb detector array, and the bandpass was set with a Barr Associates K filter. A total of 45 images, each exposed for 60 s, were taken in a 3 × 3 grid and then shifted and co-added using standard IR observing techniques. Conditions were once again not photometric, and our magnitude scale has been set by star A, for which $K = 16.95$ (Chary 1997).

At the location of the GRB counterpart we find a 1 σ positive deviation of 28 detected electrons, corresponding to $K = 19.7$. This does not constitute a detection, so we quote a 4 σ upper limit of $K > 18.2$ for the GRB counterpart. This corresponds to a flux at 2.2 μ of less than 35 μJy (Wamsteker 1981; Zombeck 1997).

3. DISCUSSION

The rms variations evident in the May 12 data for GRB 970508 are 6%, and for the nearby stars A and B are 7% and 9%, respectively. The difference in the observed rms variations is unlikely to be a result of any intrinsic differences in the objects but is more likely a statistical fluctuation caused by the modest number of data points (11). We therefore set a conservative upper limit to any variation in the GRB counterpart on timescales between 10 and 70 minutes of ≲9%.

The apparent cosmological distance to GRB 970508 lends credence to the fireball models for gamma-ray bursts (Goodman 1986; Cavallo & Rees 1978; Rees & Mészáros 1992). In these models the blast wave accelerates outward with high Lorentz factor. The optical luminosity comes from the interaction of the blast wave with the surrounding interstellar medium (Mészáros, Rees, & Wijers 1997; Vietri 1997; Sari, Piran, & Narayan 1997). The GRB was detected on May 8.904 (Costa et al. 1997) so that by May 12 the predicted size of the blast wave was ∼3 lt-days. Thus, the fireball model is consistent with our observed lack of short timescale variability on May 12.

Some authors have indicated that the optical decay of GRB 970508 (Sokolov et al. 1997), and also of GRB 970228 (Galama et al. 1997), was not well described by a single power-law decay. In order to test this possibility, we have fitted power-law decay models, $f = a * t^{-\alpha}$, to the flux densities derived from the magnitudes in this Letter and reported in the literature. For GRB 970508 we use the magnitudes reported by Sokolov et al. (1997, 1998), which include measurements from the 6 m SAO RAS, Keck (Metzger, Cohen, & Chaffee 1997a), and Palomar (Djorgovski et al. 1997) observatories, transformed to a common R_C bandpass. To these we added R_C and R measurements from the NOT (Pedersen et al. 1998), the WIYN, WHT, CAHA, and Loiano Observatories (Galama et al. 1998; Castro-Tirado et al. 1998a; Schaefer et al. 1997; Castro-Tirado et al. 1998b), from Haute-Provence (Chevalier & Ilovaisky 1997) and the *Hubble Space Telescope* (*HST*) (Fruchter, Bergeron, & Pian 1997a), corrected (when necessary) to the zero point determined by Sokolov et al. (1998). The magnitudes of Castro-Tirado et al. (1998a) have been corrected to the scale of Sokolov et al. (1998) by subtracting 0.2 mag (J. Gorosabel 1998, private communication). These magnitudes are listed in Table 2. The corresponding fluxes (Allen 1973) are shown in Figure 1. The fits do not include the data during the rise of the optical transient (i.e., prior to the maximum on May 10.77), nor after the host galaxy clearly contributes significantly (after August 27). The best-fit $\alpha = 1.19$, but the formal $\chi^2 = 85$ for 43 degrees of freedom. Clearly, a single power-law (alone) is not an adequate description of the decay.

Motivated by the comments of Fruchter et al. (1997b), we then excluded all points lying more than 2.5 σ away from the fit (see Table 2). The remaining 37 points are well fitted ($\chi^2 = 48$) by a single power law with $\alpha = 1.19 \pm 0.02$ (68% limits, 90% limits are ± 0.03). We note that the slope we find is 2.2 σ and 0.9 σ different from those found by Sokolov et al. (1998) and Galama et al. (1998), respectively, perhaps as a result of slightly differing data sets. The outliers are from data sets that otherwise appear to fit the curve, which argues that they are not caused by calibration differences but are instead real fluctuations in the decay light curve. This also argues that any difference between R and R_C magnitudes is smaller than the typical error bar. Galama et al. (1998) measure the magnitude of these fluctuations to be ∼15%, consistent with our findings.

The last two data points included in these fits (from August 14.18 and August 26.99) are both more than 3 σ above the power-law fit, indicating that the underlying galaxy may be contributing significantly to the detected flux. Recent observations at Keck (Bloom et al. 1998) and WHT (Castro-Tirado et al. 1998b) and the SAO (Zharikov et al. 1998) confirm the existence of a steady component. A power-law plus constant source fit to the data in Table 2 (excluding the same outliers) finds a decay slope $\alpha = 1.22 \pm 0.03$ and a constant source with $R_C = 25.6 \pm 0.3$. This is consistent with the magnitude found by Zharikov et al. (1998).

We then repeated the same procedure with the data for GRB 970228 from Galama et al. (1997) and Fruchter et al. (1997b). Reducing this data to a common set of R_C magnitudes for the GRB optical counterpart is complicated by the surrounding nebulosity. The most recent *HST* measurement of this nebulosity finds $V = 25.6 \pm 0.25$ (Fruchter et al. 1997b), so we have corrected the ground-based magnitudes for this refined estimate of the nebular contribution. We have assumed that the color of the nebulosity does not change, and therefore the $V - R = 0.35$ reported by Galama et al. (1997) indicates $R_{neb} = 25.25 \pm 0.25$. The measurement of Guarnieri et al.

TABLE 2

$R_{C,R}$ Magnitudes for GRB 970508

Date (UT)	Magnitude	Observatory	References
May 9.128	21.20 ± 0.1[a]	CAHA	1
May 9.195	21.08 ± 0.15[a]	P200	2, 3
May 9.20	21.25 ± 0.05[a]	WIYN	4
May 9.75	21.19 ± 0.25[a]	SAO	5
May 9.85	21.13 ± 0.18[a]	SAO	5
May 9.899	20.7 ± 0.1[a]	CAHA	1
May 9.93	20.88 ± 0.05[a]	WHT	4
May 10.03	20.46 ± 0.05[a]	WHT	4
May 10.142	20.09 ± 0.02[a]	WIYN	6, 3
May 10.178	19.93 ± 0.09[a]	P200	2, 3
May 10.77	19.70 ± 0.03	SAO	5
May 10.850	19.6 ± 0.1	LOIANO	1
May 10.872	19.6 ± 0.2	CAHA	1
May 10.93	19.80 ± 0.03	SAO	5
May 10.98	19.92 ± 0.05	WHT	4
May 11.01	19.77 ± 0.07[b]	WHT	4
May 11.144	19.9 ± 0.1	WHT	1
May 11.198	19.87 ± 0.10	P60	2, 3
May 11.76	20.10 ± 0.03	SAO	5
May 11.868	20.2 ± 0.1	CAHA	1
May 12.03	20.30 ± 0.07[b]	WHT	4
May 12.135	20.26 ± 0.03	WIYN	6, 3
May 12.139	20.3 ± 0.1	CAHA	1
May 12.203	20.25 ± 0.02	WO	7
May 12.195	20.28 ± 0.12	P60	2, 3
May 12.87	20.63 ± 0.05	SAO	5
May 13.179	20.50 ± 0.15	P200	2, 3
May 13.850	20.3 ± 0.1[b]	LOIANO	1
May 13.88	21.09 ± 0.07[b]	SAO	5
May 14.167	21.05 ± 0.07	WO	7
May 14.400	20.9 ± 0.2	Haute-Provence	8, 3
May 14.860	21.3 ± 0.2	LOIANO	1
May 14.979	21.25 ± 0.05	NOT	9
May 16.884	21.51 ± 0.10	NOT	9
May 19.051	21.88 ± 0.25	NOT	9
May 19.185	21.92 ± 0.10	NOT	9
May 20.875	21.81 ± 0.10	SAO	5
May 21.892	22.09 ± 0.07	SAO	5
May 22.97	22.04 ± 0.07	WHT	4
Jun 01.912	23.10 ± 0.07	NOT	9
Jun 2.59	23.1 ± 0.15	*HST*	10, 3
Jun 5.26	23.2 ± 0.20	KECK	11, 3
Jun 7.879	23.52 ± 0.10[b]	NOT	9
Jun 7.917	23.66 ± 0.10[b]	SAO	5
Jun 8.991	23.54 ± 0.20	SAO	5
Jun 10.928	23.34 ± 0.20	SAO	5
Jun 13.966	23.42 ± 0.14	SAO	5
Jun 14.9261	23.50 ± 0.25	NOT	9
Jun 27.893	23.88 ± 0.16	SAO	5
Jul 4.19	23.95 ± 0.20	WHT	4
Jul 7.946	24.08 ± 0.20	SAO	5
Jul 31.843	24.54 ± 0.25	SAO	5
Aug 2.807	24.28 ± 0.35	SAO	5
Aug 14.18	24.28 ± 0.10[b]	NOT	9
Aug 26.90	24.57 ± 0.07[b]	WHT	4
Oct 9.94	24.30 ± 0.20[a]	SAO	12
Nov 10.04	24.70 ± 0.15[a]	SAO	12
Nov 25.97	24.70 ± 0.14[a]	SAO	12
Nov 29	25.09 ± 0.14[a]	KECK	13
Jan 24.87	24.96 ± 0.17[a]	SAO	12
Feb 22.4	25.29 ± 0.16[a]	KECK	13
Mar 20.5	25.20 ± 0.25[a]	WHT	14

[a] Data obtained during the rise, or after the host galaxy dominates, and excluded from the power-law fit.

[b] Outlier dropped from power-law fit.

References.—(1) Castro-Tirado et al. 1998a; (2) Djorgovski et al. 1997; (3) Sokolov et al. 1997; (4) Galama et al. 1998; (5) Sokolov et al. 1998; (6) Schaefer et al. 1997; (7) this Letter; (8) Chevalier & Ilovíasky 1997; (9) Pedersen et al. 1998; (10) Fruchter et al. 1997b; (11) Metzger et al. 1997b; (12) Zharikov et al. 1998; (13) Bloom et al. 1998; (14) Castro-Tirado et al. 1998b.

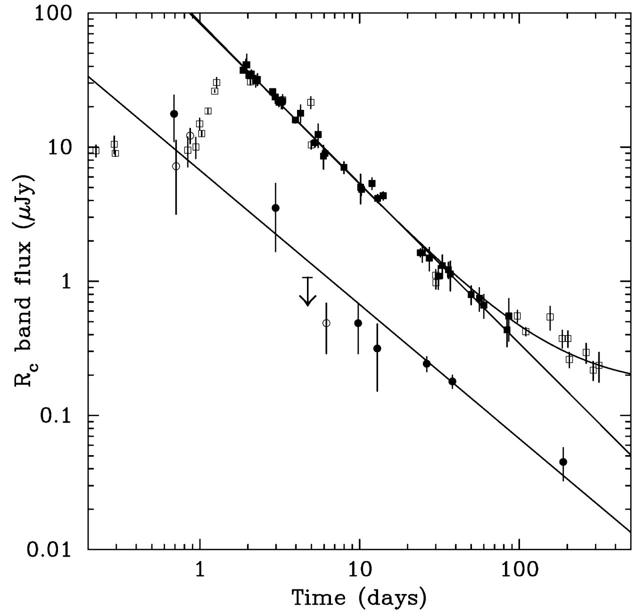

Fig. 1.—R_C-band light curves of GRB 970228 (*circles, lower line*) and GRB 970508 (*boxes, upper line*) and best-fit power-law decays of $\alpha = 1.0$ and $\alpha = 1.19$, respectively. Points that have been excluded from the power-law fits are drawn as open symbols, those included are drawn as filled symbols. The curved line is the best fit to a power law plus constant and shows that the host galaxy in GRB 970508 has been detected at a magnitude of $R_C = 25.6 \pm 0.3$. The decays for both GRB are statistically consistent with power-law decays with $\alpha = 1.2$ plus occasional small excursions.

(1997) took place in poor seeing and therefore needs an additional correction because of contamination by a nearby late type star with $R = 22.4 \pm 0.3$. (We note that this measurement took place on February 28.83, not February 28.76 as reported in Galama et al. 1997.) The most recent *HST* measurement of the optical counterpart finds $V = 28.0 \pm 0.25$. We followed the method of Galama et al. in order to convert this V magnitude to the R_C band. Because the GRB 970228 optical transient became redder during the decay, we assumed a value of $V - R = 1.0$, redder by 0.1 than the proceeding *HST* points, and we included the suggested 0.1 mag uncertainty in the conversion (Galama et al. 1997). For the purposes of computing χ^2, we treated the upper limit from March 04.86 as a detection 1 mag below the limit, with a 1 mag error. The fluxes and errors from the literature are listed in Table 3.

A power-law fit to all 11 data points gives $\alpha = 1.04$, but

TABLE 3

R_C Magnitudes for GRB 970228

Date (UT)	Magnitude	Observatory	References
Feb 28.81	20.5 ± 0.5	RAO	1
Feb 28.83	$21.5^{+0.7}_{-0.5}$[a]	BUT	2
Feb 28.99	20.92 ± 0.15[a]	WHT	1
Mar 3.10	$22.3^{+0.8}_{-0.7}$	APO	1
Mar 4.86	>23.4	NOT	1
Mar 6.32	$24.4^{+0.5}_{-0.4}$[a]	KECK	1
Mar 9.90	$24.4^{+0.5}_{-0.4}$	INT	1
Mar 13.00	$24.9^{+0.8}_{-0.4}$	NTT	1
Mar 26.42	25.17 ± 0.13	*HST*	1
Apr 7.23	25.50 ± 0.13	*HST*	1
Sep 4.7	27.00 ± 0.35	*HST*	3

[a] Outlier excluded from power-law fits.

References.—(1) Galama et al. 1997; (2) Guarnieri et al. 1997; (3) Fruchter et al. 1997b.

the resulting $\chi^2 = 19.4$ shows that this fit is an unacceptable description of the data. Removing the outlier(s) from the fit does produce an acceptable χ^2, but unlike GRB 970508, the results of the fits are dependent upon *which* outlier(s) are removed from the fit. For example, Fruchter et al. (1997b) note that the points at March 04.86 and March 06.32 lie below the fit, and excluding them produces an acceptable power-law fit. Our results agree, in that merely removing the point from March 06.32 produces an acceptable fit with $\chi^2 = 10.0$ and yields $\alpha = 1.08^{+0.09}_{-0.12}$ (90% errors). The point that suffers most from contamination by surrounding light is that reported by Guarnieri et al. (1997), but it appears to be consistent with this fit. Removing this point as well results in an insignificant reduction in the scatter to $\chi^2 = 8.1$ (9 points) and yields $\alpha = 1.11^{+0.10}_{-0.12}$ (90%). The single point that has the largest effect on the scatter is that from February 28.99, and removing it alone gives a $\chi^2 = 5.05$ (10 points) and yields $\alpha = 0.75^{+0.22}_{-0.21}$ (90%).

We conclude that the decay of GRB 970228, like that of GRB 970508, can be well described by a single power law, with superposed fluctuations. However, perhaps because of the smaller numbers of points involved, the slope of the decay is not as well determined, and we conservatively estimate $\alpha = 1.0^{+0.2}_{-0.5}$ (90%). Alternatively, one may choose to describe the decay as two separate power laws with different slopes (Masetti et al. 1997). We note that the slope we find is consistent with that found by Masetti et al. (for the long-term trend) and Fruchter et al. (1997b).

The spectral slope of the GRB 970508 decay has been measured in the optical (4000–6000 Å) to be approximately $F_\nu \sim \nu^{-1}$ (Metzger et al. 1997b; Djorgovski et al. 1997), as predicted in the fireball models (Mészáros & Rees 1997). Interpolating between the measured R_C fluxes to the time of our K measurement, this spectral slope predicts a flux at 2.2 μ of 16 μJy, well below our measured upper limit of less than 35 μJy.

In its simplest form, the impulsive cosmological fireball model (see, e.g., Mészáros & Rees 1997) predicts a single power-law decay. Given that the light curves of these two GRB optical counterparts have been measured for more than 100 days, it is remarkable that, with the exception of a few fluctuations, they can both be fitted with a single power law of slope $\alpha = 1.2$. In the context of the cosmic fireball models, these fluctuations could be caused by inhomogeneities in the swept-up interstellar medium, or sporadic additional energy input into the shock front. Given the small number of GRB light curves measured, we feel it is too early to know whether the power-law slope of $\alpha = 1.2$ is a generic feature of GRB all optical counterparts, or merely particular to these two. If it is a generic feature, then it would argue against a beamed fireball, because beaming produces a wide variety of power-law decay slopes depending upon the degree and direction of the beaming (Mészáros et al. 1997).

It therefore may be appropriate to consider spherically symmetric models for the GRB afterglow. In these models the power-law decay slope is an indication of either the run of density with radius of the swept-up medium (Mészáros et al. 1997; Vietri 1997), or of the shape of the electron energy distribution (Sari, Piran, & Narayan 1997).

In the spherically symmetric models of Mészáros et al. (1997), the density of the swept-up medium (ρ) as a function or radius (r) is parameterized as $\rho \sim r^{-n}$, and the exponent n can be written as a function of the decay slope and spectral index. If the afterglow is radiative, the decay slope of $\alpha = 1.2$ and the spectral index $F_\nu \sim \nu^{-1}$ (as measured in GRB 970508; Metzger et al. 1997b) imply $\rho \sim r^{-2.7}$ (Mészáros et al. 1997, eq. [5]). However, the fireball is expected to quickly become adiabatic. Under the expected conditions of an adiabatic fireball and weak coupling between the electrons and protons (Mészáros et al. 1997, eq. [8]), it is difficult to produce decay slopes of $\alpha = 1.2$ with density gradients that might be expected in the ISM. Typical ISM density gradients would produce slopes of $\alpha = 1.0$, or slopes steeper than $\alpha = 1.5$, in the spherically symmetric case.

The models of Sari, Piran, & Narayan (1997) assume a spherically symmetric fireball sweeping up an ISM of uniform density, but include the effects of a power-law distribution of electron Lorentz factors $\gamma_e \sim \gamma_e^{-p} d\gamma_e$. These models can reproduce the observed decay slope of $\alpha = 1.2$ for $p = 2.6$, assuming that the optical frequencies correspond to the "low-frequency" regime, and assuming that our measurements occur at time t such that $t_m < t < t_c$. The power-law decay should change slope at these critical times, and the fact that no change is seen implies that $t_c \gtrsim 100$ days. We note that the X-ray decay of some GRBs may be steeper than $\alpha = 1.2$.[7] In the context of the model of Sari et al. (1997), this could indicate that the X-rays are in the "high-frequency" regime, while the optical decay is indicative of the "low-frequency" regime.

We note that *AXAF*, working in conjunction with satellites designed to discover GRBs, may be able to provide ~1″ positions for GRB counterparts and also measure both the X-ray spectrum and decay slope to higher accuracy than has previously been possible. This should facilitate the search for additional optical and radio counterparts and should allow careful testing of models for GRB afterglows.

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[7] See the Huntsville GRB Symposium Proceedings at http://crow.riken.go.jp/˜ayoshida/grb.html, compiled by A. Yoshida.

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