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THE RAPIDLY FADING OPTICAL AFTERGLOW OF GRB 980519

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ABSTRACT

GRB 980519 had the most rapidly fading of the well-documented gamma-ray burst (GRB) afterglows, consistent with $t^{-2.05\pm0.04}$ in *BVRI* as well as in X-rays during the 2 days in which observations were made. We report *VRI* observations from the MDM 1.3 m and WIYN 3.5 m telescopes, and we synthesize an optical spectrum from all of the available photometry. The optical spectrum alone is well fitted by a power law of the form $\nu^{-1.20\pm0.25}$, with some of the uncertainty due to the significant Galactic reddening in this direction. The optical and X-ray spectra together are adequately fitted by a single power law, $\nu^{-1.05\pm0.10}$. This combination of steep temporal decay and flat broadband spectrum places a severe strain on the simplest afterglow models involving spherical blast waves in a homogeneous medium. Instead, the rapid observed temporal decay is more consistent with models of expansion into a medium of density $n(r) \propto r^{-2}$, or with predictions of the evolution of a jet after it slows down and spreads laterally. The jet model would relax the energy requirements on some of the more extreme GRBs, of which GRB 980519 is likely to be an example because of its large gamma-ray fluence and faint host galaxy.

Subject heading: gamma rays: bursts

1. INTRODUCTION

The localization of gamma-ray bursts (GRBs) by the Wide-Field Camera (WFC) on the *BeppoSAX* satellite (Boella et al. 1997) has enabled rapid and detailed follow-up studies to be made at other wavelengths, including X-ray (Costa et al. 1997), optical (van Paradijs et al. 1997), and radio (Frail et al. 1997). Perhaps the most important result of this breakthrough has been the measurement of cosmological redshifts for five bursts (Metzger et al. 1997; Kulkarni et al. 1998, 1999; Djorgovski et al. 1998b, 1999) and the detection of faint host galaxies for these five plus four other bursts, leading to the conclusion that the majority of, if not all GRBs, are the most energetic events in the universe.

GRB 980519 was one of the brightest in the *BeppoSAX* WFC (Muller et al. 1998; in 't Zand et al. 1999), second only to GRB 990123 (Feroci et al. 1998). The onset of 2–27 keV emission from GRB 980159 in the WFC preceded the BATSE trigger on May 19.514035 UT by about 70 s (in 't Zand et al. 1999), a phenomenon which characterizes only a few percent of bursts. The BATSE measured fluence above 25 keV was $(2.54 \pm 0.41) \times 10^{-5}$ ergs cm^{-2}, among the top 12% of BATSE bursts (Connaughton 1998). An X-ray observation with the *BeppoSAX* Narrow-Field Instruments (NFIs) began 9.7 hr after the burst (Nicastro et al. 1998) and detected an afterglow with a 2–10 keV flux of $(3.8 \pm 0.6) \times 10^{-13}$ ergs cm^{-2} s^{-1} in the first 4 hr, which faded by about a factor of 4 in the 1.2 days following.

The optical afterglow of GRB 980519 was discovered by Jaunsen et al. (1998) 8.8 hr after the burst using the 2.5 m Nordic Optical Telescope (NOT). Initially estimated at magnitude $I = 19.5$, this was the first optical afterglow to appear brighter than the limiting magnitude of the Palomar Sky Survey, thus enabling immediate recognition. Djorgovski et al. (1998a) confirmed the optical transient (OT) and noted that its decay was consistent with $t^{-1.98}$. Kemp & Halpern (1998) obtained additional photometry and calibrations which showed that the initial NOT detection was actually brighter than first suggested ($I = 18.4$, see below). VLA observations within the first 3 days (Frail, Taylor, & Kulkarni 1998) detected a variable 8.3 GHz source at the position of the OT. Submillimeter observations at the James Clerk Maxwell Telescope 8 days after the burst yielded only upper limits (Smith et al. 1999). Two months after the burst, deep optical observations detected a faint coincident object of magnitude $R = 26.05 \pm 0.22$ (Sokolov et al. 1998) or $R = 26.1 \pm 0.3$ (Bloom et al. 1998a), which is presumed to be the GRB host galaxy. Its redshift has not been determined.

2. OPTICAL OBSERVATIONS

We obtained *I* and *R* photometry of GRB 980519 on the MDM Observatory 1.3 m telescope and a *V* image on the Wisconsin-Indiana-Yale-NOAO (WIYN) 3.5 m telescope, both on Kitt Peak. Figure 1 shows the *R*-band image and the *BeppoSAX* NFI error circle. We measure a position for the OT of (J2000) $23^{h}22^{m}21^{s}.49$, $+77°15'43''.3$, with an error radius of $0''.35$. This is consistent with the radio position reported by Frail et al. (1998). Exposure times were 6×600 s in *I* and 6×300 s in *R*. The sky was reasonably clear during the MDM observations, where we also obtained calibrations using the standard star field of PG 0918+029 (Landolt 1992). Conditions started to deteriorate soon thereafter, when a single uncalibrated 600 s *V* image was obtained at WIYN. The results of these observations are listed in Table 1. Also listed is all available photometry from other observatories. Some of these observations were obtained with independent calibrations, and some were reported with respect to comparison stars calibrated by others. We have done our best to convert all of the reported magnitudes to a common system in Table 1. During this campaign three different calibrations were employed, those of

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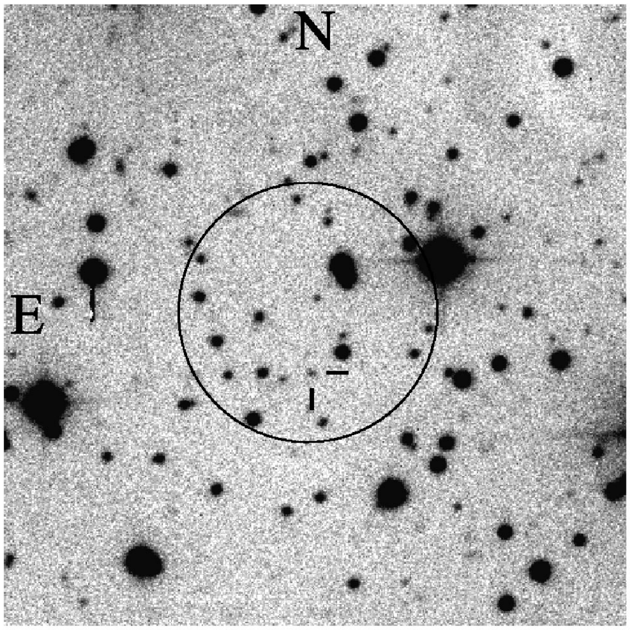

FIG. 1.—"Finding chart" for the GRB 980519 optical transient made from the MDM 1.3 m *R*-band image of May 20.31, where $R_{OT} = 20.76$. A $4' \times 4'$ section of the image is displayed. The *BeppoSAX* NFI error circle of radius 50″ (Nicastro et al. 1998) is indicated. The position of the OT is (J2000) $23^h22^m21^s.49$, $+77°15'43''.3$.

MDM (Kemp & Halpern 1998), Palomar (Bloom et al. 1998b; Gal et al. 1998), and the US Naval Observatory (USNO; Henden et al. 1998). Since the USNO calibration set is the most complete and was obtained on photometric nights with Landolt standards, we have chosen to adopt this system. We find that in *I* and *R*, the MDM magnitudes of comparison stars are fainter than those of the USNO by 0.10, while the Palomar magnitudes are fainter by 0.07. In *V* the Palomar magnitudes are brighter than those of the USNO by 0.2, while in *B* Palomar is brighter by 0.14. Accordingly, these corrections have been applied to the published magnitudes.

In Figure 2 we graph the light curves in four bands using the data from Table 1. For clarity, upper limits are not plotted since they do not contribute any additional constraints. Also not plotted are the unfiltered magnitudes of Maury, Albanese, & Boer (1998), although these are roughly consistent with the *R*-band light curve. All of the bands are consistent with the same power-law decay, $t^{-2.05\pm0.04}$. The solid lines represent the best fit to a single decay constant, with only the normalization adjusted for each band. We note that the power-law decay index of the X-ray afterglow, $\delta_x = -2.07 \pm 0.11$ as reported by Owens et al. (1998), is consistent with the optical and that these are contemporaneous observations.

3. CONTINUUM SHAPE AND REDDENING

It is possible to synthesize a *BVRI* spectrum from these data by interpolating the magnitudes to a particular time. We chose a time of May 20.34 UT, 19.8 hr after the burst, because it coincides with the largest number of measurements and because the resulting spectrum can be compared with the X-ray flux from the simultaneous *BeppoSAX* follow-up. The interpolated *BVRI* magnitudes were converted to fluxes using the effective wavelengths and normalizations of Fukugita, Shimasaku, & Ichikawa (1995) and are graphed as filled circles in Figure 3.

TABLE 1
OPTICAL PHOTOMETRY OF GRB 980519

Date (1998 UT)	Telescope	Filter	Magnitude	Reference
May 19.88	NOT 2.5 m	*I*	18.38 ± 0.1	1
May 20.00	NOT 2.5 m	*I*	18.95 ± 0.03	1
May 20.31	MDM 1.3 m	*I*	20.05 ± 0.07	2
May 20.43	Palomar 5 m	*I*	20.79 ± 0.11	3
May 20.98	NOT 2.5 m	*I*	21.54 ± 0.2	1
May 21.17	NOT 2.5 m	*I*	21.54 ± 0.1	1
May 21.35	Yerkes 41 inch	*I*	21.8 ± 0.3	4
May 21.43	Palomar 5 m	*I*	>21.5 ± 0.7	5
May 20.163	USNO 40 inch	*R*	20.39 ± 0.12	6
May 20.229	USNO 40 inch	*R*	20.77 ± 0.15	6
May 20.287	USNO 40 inch	*R*	20.87 ± 0.13	6
May 20.31	MDM 1.3 m	*R*	20.76 ± 0.07	2
May 20.4	MRO 0.76 m	*R*	21.00 ± 0.25	7
May 20.44	APO 3.5 m	*R*	21.10 ± 0.03	8
May 20.445	USNO 40 inch	*R*	21.15 ± 0.13	6
May 20.48	Palomar 5 m	*R*	21.50 ± 0.09	3
May 21.469	Palomar 5 m	*R*	23.41 ± 0.20	5
May 21.6	Keck II 10 m	*R*	23.03 ± 0.13	5
Jul 18.5	Keck II 10 m	*R*	26.1 ± 0.3	9
Jul 24	BTA 6 m	*R*	26.05 ± 0.22	10
May 20.34	WIYN 3.5 m	*V*	21.56 ± 0.08	2
May 20.466	Palomar 5 m	*V*	21.94 ± 0.16	5
May 21.476	Palomar 5 m	*V*	>22.2	5
May 20.057	Wise 1 m	*B*	21.09 ± 0.25	11
May 20.449	Palomar 5 m	*B*	22.67 ± 0.14	5
May 21.448	Palomar 5 m	*B*	>23.0	5
May 19.863	OCA 0.9 m	None	19.06 ± 0.26	12
May 20.077	OCA 0.9 m	None	19.81 ± 0.37	12
May 20.964	OCA 0.9 m	None	22.06 ± 0.76	12

REFERENCES.—(1) Hjorth et al. 1998; (2) this paper; (3) Bloom et al. 1998b; (4) Castander et al. 1998; (5) Gal et al. 1998; (6) Vrba et al. 1998; (7) Diercks & Morgan 1998; (8) Diercks & Stubbs 1998; (9) Bloom et al. 1998b; (10) Sokolov et al. 1998; (11) Leibowitz & Ibbetson 1998; (12) Maury et al. 1998.

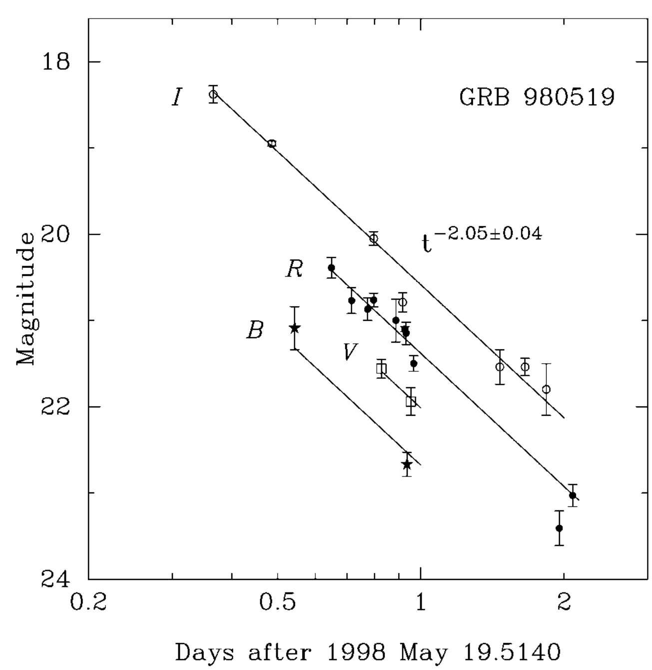

FIG. 2.—Light curves of GRB 980519 in *BRVI*. The data are taken from Table 1. Upper limits and unfiltered observations have been omitted for clarity.

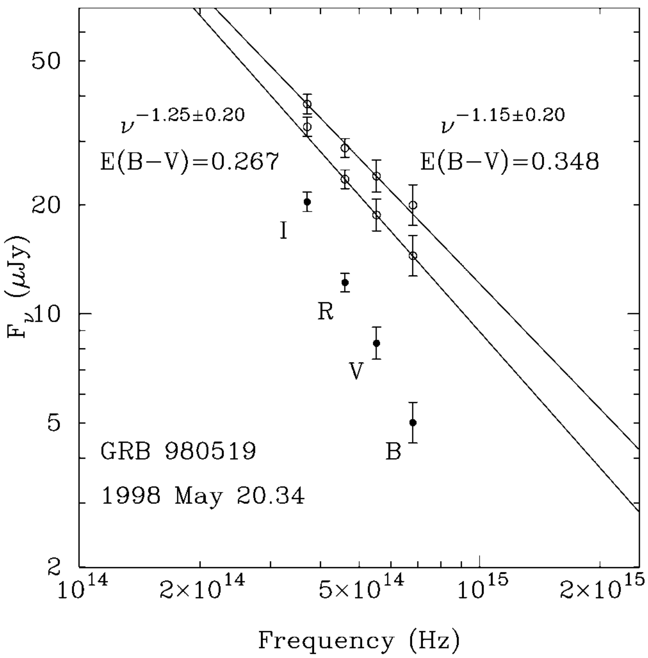

FIG. 3.—Synthetic spectrum of GRB 980519 19.8 hr after the burst, constructed from the fits in Fig. 2 (*filled circles*). Two different estimates of the Galactic extinction, as described in the text, are used to deredden the fluxes (*open circles*), which leads to slightly different power-law fits.

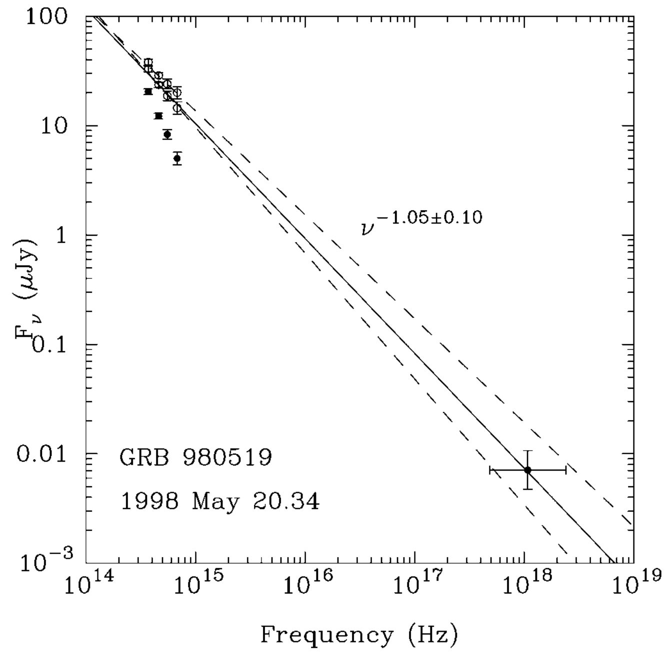

FIG. 4.—Broadband view of the spectrum of GRB 980519 19.8 hr after the burst, including the *BeppoSAX* NFI X-ray flux. As in Fig. 3, two different estimates of the Galactic extinction are used to deredden the optical fluxes. The X-ray flux is calculated from the 2–10 keV data in Nicastro et al. (1998) and Owens et al. (1998) and is assigned an uncertainty of ±50%. The dashed lines represent the estimated uncertainty on the optical–to–X-ray spectral index, $\alpha_{ox} = -1.05 \pm 0.10$.

Galactic reddening is a significant factor in this field because of its intermediate Galactic latitude: $(\ell, b) = (117^\circ.963, +15^\circ.285)$. The selective extinction $E(B-V)$ can be estimated in at least two ways. First is the value of Schlegel, Finkbeiner, & Davis (1998) from the *IRAS* 100 μm maps, $E(B-V) = 0.267$ mag. This is somewhat different from a second estimate, $E(B-V) = 0.348$ mag, which can be derived from the Galactic 21 cm column density in this direction, $N_{\rm H\,I} = 1.74 \times 10^{21}$ cm^{-2} (Stark et al. 1992), and the standard conversion $N_{\rm H\,I}/E(B-V) = 5.0 \times 10^{21}$ cm^{-2} mag^{-1} (Savage & Mathis 1979). Figure 3 shows the results of applying each of these corrections, using the relative extinctions from Schlegel et al. (1998). In either case, the spectrum is a good fit to a power law of the form $F_\nu \propto \nu^\alpha$. The smaller extinction requires $\alpha = -1.25 \pm 0.20$, while the larger extinction corresponds to $\alpha = -1.15 \pm 0.20$. Regarding these two choices as indicative of the range of systematic error, we adopt $\alpha = -1.20 \pm 0.25$ as a final result and uncertainty.

Although there is no strong evidence of additional reddening intrinsic to the afterglow, one cannot rule out small amounts that are comparable to the systematic uncertainties in the Galactic value. An additional constraint on the total extinction can be obtained in a weakly model-dependent way by comparing the extrapolated optical spectrum to the simultaneous X-ray flux as measured by the *BeppoSAX* NFI. If the synchrotron afterglow models have any validity, then the optical–to–X-ray spectral index $\alpha_{\rm OX}$ should be less than or equal to the $\alpha = -1.20 \pm 0.25$ measured in the optical band alone. That is, if there are any breaks in the broadband spectrum, they should be concave downward. In order to make this comparison, we must estimate the X-ray flux at the fiducial time of the synthesized optical spectrum. The X-ray afterglow spectrum is fit by energy index $\alpha_x = -1.52^{+0.70}_{-0.57}$ (Owens et al. 1998). Using this index, we convert the flux of $(3.8 \pm 0.6) \times 10^{-13}$ ergs cm^{-2} s^{-1} measured in the 2–10 keV band in the interval between 9.7 and 13.7 hr after the burst (Nicastro et al. 1998) to a flux of 0.021 μJy at 4.5 keV. The X-ray temporal decay of GRB 980518, $\delta_x = -2.07 \pm 0.11$, is the fastest of the seven afterglows that were well measured by *BeppoSAX* (Owens et al. 1998). From this temporal decay, we infer that by $t = 19.8$ hr the flux had faded by a factor of 3 to 0.007 μJy. Figure 4 shows the broadband optical–to–X-ray spectrum at $t = 19.8$ hr estimated in this manner. We allow for an uncertainty of ±50% on the X-ray flux in this crude analysis. The optical spectrum and its uncertainties in extrapolation are consistent with the X-ray flux, and jointly they prefer $\alpha_{\rm OX}$ of about −1.05. We conclude that any intrinsic optical extinction is small and that a single power law is a marginally consistent description of all the available optical through X-ray data. We therefore adopt $\alpha_{ox} = -1.05 \pm 0.10$ as an observed constraint on models.

4. INTERPRETATION AND CONCLUSIONS

Other bursts with well-measured light curves have δ in the range −1.1 to −1.2 (Bloom et al. 1998c; Diercks et al. 1998; Reichart et al. 1999). The GRB 980519 data described here provide the one case of a steep ($t^{-2.05}$) afterglow decay that is well documented at several frequencies. Therefore, the continuum spectral shape, together with the temporal decay, can be used to test afterglow models that relate these two quantities. In the simplest form of the external relativistic blast wave model (Mészarós & Rees 1997; Wijers, Rees, & Mészarós 1997), electrons accelerated to a power-law energy distribution proportional to E^{-p} are responsible for a decaying synchrotron spectrum of the form $F_\nu \propto \nu^\alpha t^\delta$. The energy index α equals $(1-p)/2$ if the cooling time is longer than the age of the shock (the adiabatic case), and it is related to the corresponding temporal decay constant as $\delta = 3\alpha/2$. Since we observe $\delta = -2.05 \pm 0.04$ all across the spectrum from optical to X-ray, we would expect a spectral slope $\alpha_{ox} = -1.37$, which is incompatible with the observed $\alpha_{ox} = -1.05 \pm 0.10$. Although the optical slope alone is consistent with $\alpha = -1.37$, such a model falls short of matching the X-ray flux by a factor of 10. Equivalently, $\alpha = -1.05 \pm 0.10$ would predict $\delta = -1.58 \pm 0.15$, which is incompatible with either the X-ray or the optical decay. If, instead, we assume that the electrons are in the "cooling" regime, for which $\alpha = -p/2$ and $\delta = (3\alpha + 1)/2$ (e.g., Sari, Piran, & Narayan 1998), then the discrepancy is even worse, since $\alpha = -1.05$ would require $\delta = -1.08$. If there is actually a cooling break *between* the optical and the X-ray at the epoch illustrated in Figure 4 or additional extinction in the GRB host galaxy, it would exacerbate the discrepancy between δ and $3\alpha/2$ in the optical.

Of course, these are idealized models involving isotropic expansion into a homogeneous medium. One modification to the model that might be more compatible with GRB 980519 is an inhomogeneous medium. Mészarós, Rees, & Wijers (1998) calculated the effects of differing power-law density distributions $n(r)$ for the shocked medium and concluded that $n(r) \propto r^{-2}$ would result in $\alpha = -1$ if $\delta = -2$. Both of these values are consistent with GRB 980519. An $n(r) \propto r^{-2}$ dependence is appropriate for a preexisting stellar wind.

Alternatively, one can consider anisotropic beaming models. As a way of ameliorating the energetics problem, it has long been hypothesized that GRBs are beamed. Although we have no redshift for GRB 980519 and therefore no handle on its energetics, the fact that its host galaxy at $R = 26.1$ ($R = 25.4$ corrected for Galactic extinction) is one of the fainter of the nine probable hosts detected so far means that it could be quite distant and energetic. [GRB 981220 has a coincident object of $R = 26.4 \pm 0.7$ (Bloom et al. 1999). Only GRB 980326 is apparently lacking a host galaxy to a limiting magnitude $R = 27.3$ (Bloom & Kulkarni 1998).] Assuming that GRB 980519 is at $z > 1$, for $H_0 = 65$ km s^{-1} Mpc^{-1} and $\Omega = 0.2$, its luminosity distance is at least 2.0×10^{28} cm, and the BATSE measured fluence of $(2.54 \pm 0.41) \times 10^{-5}$ ergs cm^{-2} corresponds to an isotropic energy of 6.3×10^{52} ergs. This number would rise to 6.1×10^{53} ergs at $z = 3$, greater than that of the highest redshift burst (GRB 971214 at $z = 3.42$), for which an isotropic energy of 3×10^{53} ergs was inferred (Kulkarni et al. 1998).

Jet models (Rhoads 1999) predict a transition from radial expansion to lateral spreading, after which the temporal decay steepens to t^{-p}. Values of p in the range 2–2.5 are expected. In a separate paper (Sari, Piran, & Halpern 1999), predictions of jet models for GRB 980519 and other afterglows are explored, under the assumption that a transition from radial to transverse expansion had already occurred before the first optical observation. We consider that the combination of the steep afterglow decay and faint and possibly distant host galaxy of GRB 980519 make it a good candidate for a jet.

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