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THE RADIO AFTERGLOW AND HOST GALAXY OF THE DARK GRB 020819

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ABSTRACT

Of the 14 gamma-ray bursts (GRBs) localized to better than 2′ radius with the SXC on *HETE-2*, only two lack optical afterglow detections, and the high recovery rate among this sample has been used to argue that the fraction of truly dark bursts is ~10%. While a large fraction of earlier dark bursts can be explained by the failure of ground-based searches to reach appropriate limiting magnitudes, suppression of the optical light of these SXC dark bursts seems likely. Here we report the discovery and observation of the radio afterglow of GRB 020819, an SXC dark burst, which enables us to identify the likely host galaxy (probability of 99.2%) and hence the redshift ($z = 0.41$) of the GRB. The radio light curve is qualitatively similar to that of several other radio afterglows and may include an early-time contribution from the emission of the reverse shock. The proposed host is a bright, $R = 19.5$ mag barred spiral galaxy, with a faint $R \approx 24.0$ mag "blob" of emission, 3″ from the galaxy core (16 kpc in projection), that is coincident with the radio afterglow. Optical photometry of the galaxy and blob, beginning 3 hr after the burst and extending over more than 100 days, establishes strong upper limits to the optical brightness of any afterglow or associated supernova. Combining the afterglow radio fluxes and our earliest *R*-band limit, we find that the most likely afterglow model invokes a spherical expansion into a constant-density (rather than stellar wind-like) external environment. Within the context of this model, a modest local extinction of $A_V \approx 1$ mag is sufficient to suppress the optical flux below our limits.

Subject headings: dust, extinction — galaxies: high-redshift — gamma rays: bursts

Online material: color figures

1. INTRODUCTION

The host galaxies of gamma-ray bursts (GRBs) at low and intermediate redshifts are predominately subluminous, low-metallicity, and dust-poor galaxies with very blue colors (e.g., Fruchter et al. 1999; Le Floc'h et al. 2003; Fynbo et al. 2003; Christensen et al. 2004). In particular, the three most nearby hosts (GRBs 980425, 030329, and 031203) are most likely metal-poor dwarf galaxies similar to the Magellanic Clouds but with intense star formation (Fynbo et al. 2000; Hjorth et al. 2003; Prochaska et al. 2004). The fact that GRB hosts are ubiquitously drawn from the population of faint, dust-poor galaxies implies that (1) such galaxies are responsible for the majority of star formation at all redshifts, (2) GRBs are preferentially caused by low-metallicity stars, or (3) the current sample is observationally biased against GRBs occurring in brighter, high-metallicity hosts.

Related to point 3 above is the nature of dark bursts, whose definition has been quite vague in the literature. It was commonly used for those GRBs that were not accompanied by detections of optical afterglows (OAs), irrespective of how inefficient the search was. It is important to reveal whether the fraction of dark bursts (as high as 60%–70%; e.g., Lazzati et al. 2002) is predominantly the result of inadequate observing strategies, or if dust and high redshift play a major role. Evidence has been mounting (Fynbo et al. 2001; Berger et al. 2002) that the former is the primary reason for such a high fraction. Recently, Jakobsson et al. (2004a) proposed a revised definition of dark bursts as those bursts that are optically subluminous with respect to the fireball model, i.e., which have an optical-to–X-ray spectral index $\beta_{\rm OX} < 0.5$. Applying this definition to a set of 52 bursts, only 10% have optical limits deep enough to establish them as dark bursts. Rol et al. (2005) obtained a comparable dark burst fraction using a more detailed analysis, albeit with a smaller sample.

In this paper we present the detection of the radio afterglow of GRB 020819 and propose that a bright spiral galaxy ($z = 0.41$) coincident with the radio position is the host. We explore the nature of the GRB external environment by applying the fireball model on the afterglow radio flux. When combined with an early optical *R*-band limit, this reveals whether host extinction needs to be invoked. We also search for a signature of a supernova (SN). Finally, we discuss GRB 020819 in the context of rapid localizations and follow-up of GRBs and its implications for dark bursts. We adopt a cosmology where the Hubble parameter is $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$. For these parameters, a redshift of 0.41 corresponds to a luminosity distance of 2.24 Gpc and a distance modulus of 41.7. One arcsecond is equivalent to 5.45 proper kiloparsecs, and the look-back time is 4.36 Gyr.

2. OBSERVATIONS

GRB 020819 was detected by the French Gamma Telescope, Wide Field X-Ray Monitor, and Soft X-Ray Camera (SXC) on

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TABLE 1
OPTICAL/NIR OBSERVATIONS OF GRB 020819

Epoch	Δt[a] (days)	Telescope/Instrument	Seeing (arcsec)	Exposure Time (s)	Filter	Magnitude[b] Galaxy	Blob	Limiting Magnitude[c]
2002 Aug 19.76	0.14	1.0 m SSO	2.5	3×300	R	19.62 ± 0.15		21.5
2002 Aug 20.34	0.72	P60	1.6	4×600	R	19.60 ± 0.11		22.1
2002 Aug 26.53	6.91	Keck/NIRC[d,e]	...	9×60	K	...	...	...
2002 Sep 03.47	14.85	Keck/ESI	0.6	7×600	B	21.90 ± 0.50	26.10 ± 0.50	26.9
2002 Sep 03.51	14.89	Keck/ESI	0.6	4×600	R	19.48 ± 0.12	23.99 ± 0.13	26.9
2002 Sep 10.09	21.47	NOT/ALFOSC	1.1	5×600	R	19.34 ± 0.06		25.3
2002 Sep 15.17	26.55	VLT/FORS2	0.7	22×300	R	19.45 ± 0.02	23.98 ± 0.06	25.8
2002 Oct 13.37	54.75	Keck/NIRC[d]	...	27×60	K	16.80 ± 0.20	20.80 ± 0.30	...
2003 Jan 01.24	134.62	Keck/ESI	0.7	$2 \times (300 + 600)$	R	19.43 ± 0.10	23.76 ± 0.15	26.6

NOTES.—The magnitudes reported here are the results of aperture photometry (see main text for details). Correction for Galactic extinction has been applied to the photometry (Schlegel et al. 1998).
[a] Measured in days after 2002 August 19.623 UT.
[b] The host galaxy and blob were not resolved in the SSO, P60, or NOT observations.
[c] Limiting magnitudes are 2 σ in a circular aperture with a radius equal to the seeing.
[d] There were no stars in the Keck/NIRC field of view to estimate the seeing and limiting magnitude.
[e] No standard star observations were available for calibration of this epoch.

board the *High Energy Transient Explorer 2* (*HETE-2*) satellite on 2002 August 19.623 UT. A 130″ radius SXC error circle was circulated 3 hr after the burst (Vanderspek et al. 2002). A few days later, its location was refined and the radius reduced to 64″, lying fully within the original error circle (Crew et al. 2002).

We observed the 130″ radius SXC error circle with the Siding Spring Observatory (SSO) 1.0 m telescope in Australia at $\Delta t = 3.1$ hr (Price & McNaught 2002), where Δt is the time from the onset of the burst. At $\Delta t = 17.3$ hr we imaged the field again with the 1.5 m telescope (P60) at Palomar (Price et al. 2002a). In neither case was an OA detected. We continued to monitor the field in the optical/NIR during the following weeks and months with the Echellette Spectrograph and Imager (ESI) and the Near Infrared Camera (NIRC) on Keck, the Andalucia Faint Object Spectrograph and Camera (ALFOSC) on the Nordic Optical Telescope (NOT), and the Focal Reducer and Low Dispersion Spectrograph (FORS2) on the Very Large Telescope (VLT). The record of our observations is listed in Table 1.

Although a rapid and deep follow-up was performed, no optical/NIR afterglow has been reported for GRB 020819. Levan et al. (2003) obtained a deep optical limit ($R = 22.2$ mag) at $\Delta t = 9$ hr, covering the original SXC error circle. During the same epoch, Klose et al. (2003) performed a NIR follow-up observation, with a limiting magnitude of $K = 19.5$ mag. Unfortunately, their analysis and afterglow search was only applied to the refined 64″ SXC error circle (see discussion in § 3.2).

We discovered (Frail & Berger 2003) a variable radio source at 8.46 GHz with the Very Large Array (VLA), declining from a peak of 315 μJy at $\Delta t = 1.75$ days to a level of nondetection at $\Delta t = 157$ days. A log of the GRB 020819 radio observations is given in Table 2. This source was located at α(J2000.0) $= 23^{\rm h}27^{\rm m}19\overset{\rm s}{.}475$ and δ(J2000.0) $= 06°15'55\overset{''}{.}95$, with an error of $0\overset{''}{.}5$ in each coordinate. The radio transient is located only 3″ away from the center of a bright barred spiral galaxy. In addition, the transient is superposed on a faint blob of light. A Keck/ESI image covering the surrounding field is displayed in Figure 1.

3. RESULTS

3.1. *Optical/NIR*

The optical data were reduced using standard techniques for debiasing and flat-fielding. In order to determine the photometric properties of the potential host galaxy and blob, we used aperture photometry. A circular aperture with a fixed radius of $4\overset{''}{.}5$ was used for all the different telescopes/instruments to obtain the total flux from the galaxy. To verify the results, we used SExtractor (Bertin & Arnouts 1996) to obtain its total magnitudes (`mag_auto`). The photometry of the nearby blob was also carried out using aperture photometry, with a circular aperture with a fixed radius of $0\overset{''}{.}8$. Only the VLT/FORS2 epoch had a simultaneous R-band observation of a Landolt (1992) standard field. We used this to calibrate secondary standards for the GRB 020819 field, which we in turn used to transform the relative optical magnitudes to the Cousins photometric system. For the B-band Keck epoch there was only one faint nonsaturated calibrated star in field from the Digitized Second Palomar Observatory Sky Survey (DPOSS). The resulting calibrated magnitude is therefore quite uncertain. We note that DPOSS uses the Gunn photometric system, which we converted to the Johnson photometric system (e.g., Jørgensen 1994).

The NIR images were dark-subtracted and flat-fielded using the object-masked average of proximate science frames. They were registered against each other by reference to the centroid position of the single bright object, the galaxy core, and co-added.

TABLE 2
VLA OBSERVATIONS OF GRB 020819

Epoch	Δt[a] (days)	$\nu_{\rm obs}$ (GHz)	$S \pm \sigma$ (μJy)
2002 Aug 21.37	1.75	8.46	315 ± 18
2002 Aug 23.34	3.72	8.46	176 ± 19
2002 Aug 23.36	3.74	1.43	39 ± 60
2002 Aug 29.32	9.70	8.46	264 ± 30
2002 Aug 29.34	9.72	4.86	224 ± 34
2002 Sep 10.27	21.65	8.46	161 ± 24
2002 Sep 18.26	29.64	8.46	109 ± 20
2002 Oct 03.17	44.55	8.46	43 ± 31
2002 Dec 24.07	126.45	8.46	79 ± 25
2002 Dec 28.02	130.40	8.46	32 ± 26
2003 Jan 10.06	143.44	8.46	62 ± 25
2003 Jan 23.90	157.28	8.46	6 ± 14

[a] Measured in days after 2002 August 19.623 UT.

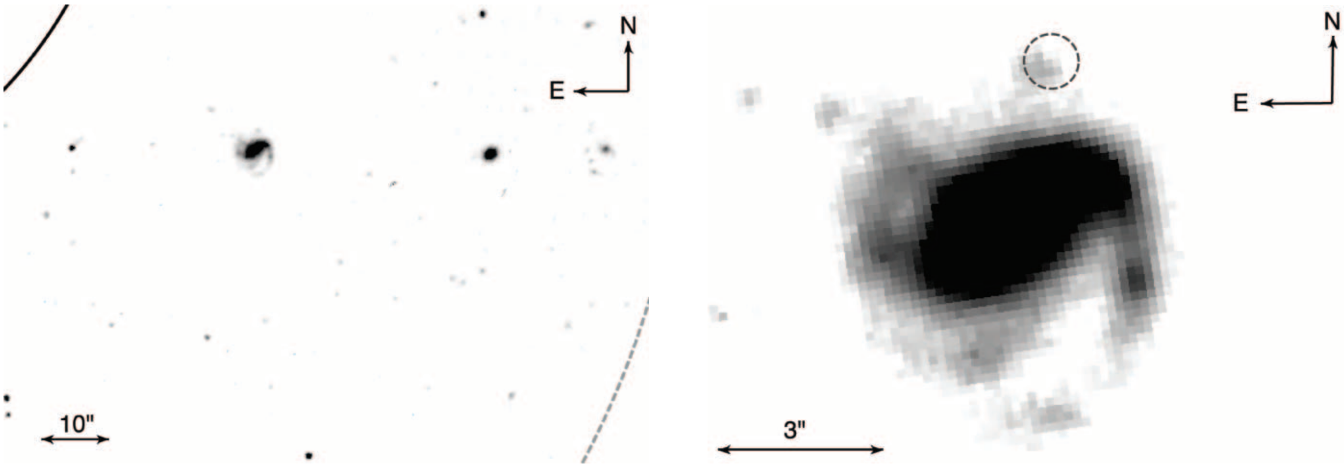

Fig. 1.—A 2400 s *R*-band Keck / ESI image of the neighborhood of the GRB 020819 radio afterglow, obtained approximately 15 days after the burst occurred. *Left*: The original 130″ radius error circle is indicated by the dashed line, while the refined one is shown with a continuous line. *Right*: A zoom-in on the position of the radio afterglow, marked with a dashed circle with a radius of 0″.5. A bright barred spiral galaxy is located around 3″ from the afterglow, which is superposed on a faint light source. The image is shown with a logarithmic intensity scale to highlight the features of the nearby blob. [*See the electronic edition of the Journal for a color version of this figure.*]

A rough World Coordinate System was put on the images using the telescope pointing and instrument rotation information as encoded in the image headers; this was later refined by reference to larger scale images of the field. Galaxy and blob fluxes were obtained with aperture photometry. For the second *K*-band epoch, we used an observation of a 2MASS star to transform the magnitudes to the standard system. Unfortunately, no standard stars were available for the first *K*-band epoch.

The results of the optical / NIR photometry are listed in Table 1. We have an early, relatively deep limit of $R > 21.5$ mag at $\Delta t = 3.4$ hr. This is fainter than the entire sample of afterglows detected and studied in the past 7 years at a similar epoch, excluding the recent GRB 050126 (see Berger et al. 2005b, Fig. 5). We note, however, that much deeper optical limits have been obtained at a similar epoch, e.g., GRB 970828 (Groot et al. 1998). Whether the GRB 020819 optical faintness is due to high redshift, host extinction, or simply an intrinsically faint GRB is a question best answered in synergy with the radio observations.

The bright barred spiral galaxy and the faint blob are clearly resolved in the Keck and VLT images. After correcting for foreground (Galactic) extinction using the reddening maps of Schlegel et al. (1998), the galaxy has $R - K = 2.7 \pm 0.2$ mag, while the nearby blob has $R - K = 3.2 \pm 0.3$ mag. To examine if a NIR afterglow contributes flux to the blob in the first *K*-band epoch ($\Delta t = 6.9$ days), we performed an image subtraction using the second *K*-band epoch. We subtracted out the galaxy and looked for residual emission from the blob. But due to the lack of stars in the field of view, the validity of the subtraction could not be confirmed. The error in the galaxy subtraction remained larger than any residual emission from the blob.

3.2. *The Radio Light Curve*

All observations were performed using the VLA in its standard continuum mode. At each frequency, the full 100 MHz bandwidth was obtained in two adjacent 50 MHz bands. The flux density scale was tied to the extragalactic source 3C 147, while the array phase was monitored by switching between the GRB and a VLA phase calibrator J2320+052 (J2330+110) at 8.46 GHz (1.43 GHz). Data calibration and imaging were carried out with Astronomical Image Processing System software package.

In an image from $\Delta t = 1.75$ days, we found an unresolved source at high significance (18 σ). Although the transient is 98″ away from the center of the revised 64″ SXC error circle, its position and radius have been revised again (Villasenor et al. 2004). It now includes the radio transient, lending support to the hypothesis that the transient is in fact the GRB afterglow. Its light curve is presented in Figure 2. It is qualitatively similar to previous radio afterglows, where the first data point is most likely due to a strong reverse shock (see a schematic light curve in Frail 2005), GRB 990123 being the best-known example (Sari & Piran 1999).

There is a sign of a late-time flattening in the radio light curve. Due to the relatively deep upper limit at $\Delta t \approx 157$ days, it is unlikely that the final radio detection at $\Delta t \approx 126$ days originates from the host galaxy. A more probable explanation is an episodic injection of energy, where slower moving shells of ejecta catch up with the decelerating main shock and re-energize it. This refreshed shock model has recently been invoked to explain the optical, X-ray, and radio behavior of GRB 021004 (Björnsson et al. 2004). We note that the flux limit of 34 μJy at $\Delta t \approx 157$ days implies an upper limit to the host star formation rate of approximately 40 $M_\odot$ yr^{-1} (see Berger et al. 2003, Fig. 1).

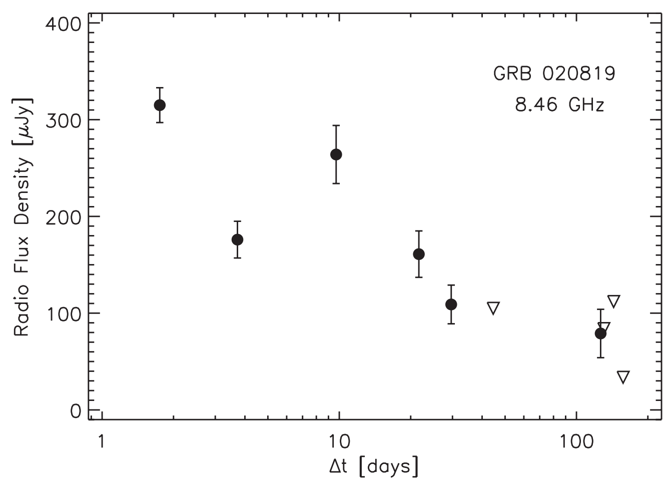

Fig. 2.—An 8.46 GHz light curve from the VLA of the radio afterglow of GRB 020819. Detections at each epoch are indicated by circles. Nondetections, shown with triangles, are defined as the peak brightness at the location of the afterglow plus 2 times the rms noise in the image.

The qualitative behavior of other radio light curves can be summarized as follows (e.g., Sari et al. 1998, Figs. 1 and 2). The flux at a given radio frequency (ν_R) rises as a power law $F_R(t) \propto t^{\alpha_r}$, reaches a broad maximum at F_m, and then decays as $F_R(t) \propto t^{\alpha_d}$. This is due to the evolution of the characteristic break frequencies in the broadband synchrotron spectrum, where, for example, the epoch of peak flux is frequency-dependent $[t_m(\nu_R)]$.

We have carried out a fit to this model, but given the paucity of our data, we fixed $t_m(8.46\ \mathrm{GHz}) = 10$ days, a typical and reasonable (Fig. 2) value. In addition, we have omitted the first and final detection (see discussion above). From the formal best fit we find $\alpha_r = 0.44 \pm 0.16$, $\alpha_d = -0.78 \pm 0.17$, with $F_m(8.46\ \mathrm{GHz}) = 271 \pm 31\ \mu\mathrm{Jy}$ ($\chi_1^2 = 0.42$, where $\chi^2_{\mathrm{dof}} = \chi^2$/degree of freedom, is the reduced χ^2 of the fit). Shifting t_m a few days on either side of our value does not substantially change the fitted parameters.

4. DISCUSSION

4.1. *The Host Galaxy*

The question whether a high redshift of the proposed host galaxy contributes significantly to the optical faintness of the afterglow is easily answered by the results of E. Berger et al. (2005, in preparation). They measure a redshift of $z = 0.41$ for the host,[11] the seventh closest thus far observed. As a comparison, the GRB 011121 afterglow ($z = 0.36$) had a radio flux of 610 μJy at 7 days (Price et al. 2002b) and $R \approx 18$ mag at 0.4 days (Garnavich et al. 2003; Greiner et al. 2003). These numbers indicate that the galaxy is a promising host candidate, although it needs to be explored whether the radio afterglow and the R-band limit are consistent with the fireball model (see § 4.2).

We have estimated the probability that the assigned host is a chance superposition and not physically related to the GRB, following Bloom et al. (2002a). As the GRB localization is good, but the position is outside the majority of the light of the spiral, we have calculated the effective radius (see Bloom et al. 2002a, eqs. [1]–[3]) as $(R_0^2 + 4R_{\mathrm{half}}^2)^{1/2}$. Here $R_0 = 3\farcs0 \pm 0\farcs1$ is the radial separation between the GRB and the presumed host, and $R_{\mathrm{half}} = 1\farcs35 \pm 0\farcs05$ is the half-light radius. This, combined with the galaxy magnitude, results in a chance superposition probability of only 0.8%.

The $R - K$ colors of galaxies provide crucial information on the importance of old stellar populations (as traced by the NIR emission), relative to the contribution of young stars dominating the optical light. Blue objects ($R - K \sim 2-3$ mag) are a sign of unobscured star-forming galaxies, while old ellipticals and dust-enshrouded starburst galaxies have large $R - K$ colors. An $R - K = 2.7$ mag is a bit higher than the mean value but within the range spanned by the sample of 15 host galaxies explored by Le Floc'h et al. (2003). A redshift of 0.41 places the host on a curve in Figure 2 in Le Floc'h et al. (2003) matching a type Scd galaxy, roughly consistent with the morphology seen in Figure 1. In general, Sc/Scd spirals display resolved H II regions (the blob being a likely candidate) and contain a larger fraction of dust and gas, which might explain the optical faintness of the afterglow. We note that all the spiral hosts observed so far are nearly face-on (GRBs 980425, 990705, 020819). Although this sample is small, it resembles SN-selected spirals that are more often observed face-on, most likely due to dust bias (e.g., Cappellaro et al. 1993).

[11] Unfortunately, there is no conclusive redshift reported for the blob.

4.2. *Afterglow Modeling*

The nature of the ambient medium in which the GRB originated can be probed with the parameters F_m, t_m, and α_d. In addition, they can be used to predict the R-band magnitude at $\Delta t = 0.14$ days. We consider three afterglow models: (1) an isotropic expansion into a homogeneous medium (Sari et al. 1998), (2) an isotropic expansion into a wind-stratified medium (Chevalier & Li 1999), and (3) a collimated expansion (jet) into a homogeneous or wind stratified medium (Sari et al. 1999).

For model 1, the fits in § 3.2 predict that the optical flux would have reached the maximum value of F_m (corresponding to $R = 17.6$ mag) at an epoch $t_m(\mathrm{opt}) = t_m(8.46\ \mathrm{GHz}) \times (\nu_R/\nu_{\mathrm{opt}})^{2/3} \approx 600$ s. The expected flux at later times would then drop by $2.5\alpha_d \log[\Delta t/t_m(\mathrm{opt})]$ mag, which for $\Delta t = 0.14$ days corresponds to 2.5 mag. In this framework, we would thus expect to detect an OA with $R = 20.1 \pm 0.6$ mag at the epoch of the first observation. Comparing this to the upper limit of $R > 21.5$ mag, only a modest amount of extinction must be invoked. The electron energy power-law index in this model is predicted to be $p = 1 - 4/3\alpha_d = 2.04 \pm 0.23$, consistent with what is usually found ($\bar{p} = 2.26$: Piro 2004).

As in model 1, the optical flux in model 2 reaches F_m at an epoch $t_m(\mathrm{opt}) \approx 600$ s. On the other hand, since the afterglow emission is weakened as the relativistic blast wave ploughs into ambient material with decreasing density, F_m is larger when extrapolated into the optical band, with $F_m \propto t^{-1/2}$. This results in an afterglow with $R \approx 13.6$ mag at 600 s, decaying to $R = 16.1 \pm 0.6$ mag at $\Delta t = 0.14$ days. This model would thus require a large host extinction. However, this model predicts $p = (1 - 4\alpha_d)/3 = 1.37 \pm 0.23$. Although such a low value for p has previously been observed in an afterglow (e.g., GRB 010222: Galama et al. 2003), we are not in favor of this model.

Finally, in model 3, the radio emission (above the synchrotron self-absorption frequency) is supposed to rise as $t^{1/2}$, reach a maximum, and then slowly decline as $t^{-1/3}$ for $t > t_{\mathrm{jet}}$, where t_{jet} is the epoch when the bulk Lorentz factor of the ejecta becomes comparable to the inverse of the opening angle of the jet. The radio flux is then expected to drop sharply as t^{-p}, when the maximum frequency falls below the observing frequency. This behavior has been observed, for example, for GRB 990510 (Harrison et al. 1999). As seen in Figure 2, the radio light curve does not show this kind of evolution. Even if we assume $t_{\mathrm{jet}} < t_m \approx 10$ days, the model predicts $p = -\alpha_d = 0.78$, a value not considered relevant in afterglow models.

4.3. *A Limit on a Supernova Contribution*

An excess of optical flux at $\Delta t \sim 15(1+z)$ days, superposed on a typical light curve power-law decay, is commonly attributed to the rise of a SN component (e.g., Galama et al. 1998; Bloom et al. 1999, 2002b). Motivated by this, we timed our R-band observations ($\Delta t \approx 15$, 21, and 27 days) for a SN search. To accommodate the spread in the observed properties of Type Ibc SNe, we have considered the highly luminous SN 1998bw associated with GRB 980425 (Galama et al. 1998), and SN 2002ap (Foley et al. 2003), which was a factor of $\sim$10 times less luminous at peak time in the rest-frame B band.

At $z = 0.41$ the observed R band corresponds to the rest-frame B band. Thus, we have transformed the B-band magnitude at peak time of the aforementioned SNe to AB magnitudes (Fukugita et al. 1995), applied the distance modulus, and the $2.5 \log(1+z)$ term (see, e.g., van Dokkum & Franx 1996). If GRB 020819 is associated with a 1998bw-like SN, we would

TABLE 3
SXC Localized *HETE-2* Gamma-Ray Bursts

GRB	$\Delta t_{\rm SXC}$ (hr)	$\Delta t_{\rm OA}$ (hr)	Mag($\Delta t_{\rm OA}$)	Δt_1 (hr)	Mag(Δt_1)	R(1 day)	z	SXC Circle Change?	References
020813	3.1	1.90	$B \sim 18.6$	0.30	CR > 16.0	20.5	1.26	Yes, OA outside	1, 2, 3, 4
020819	3.0	...	...	2.98	$R > 18.9$	>22.0	...	Yes, RA inside	5, 6
021004	2.6	0.05	$R = 15.5$	0.05	$R = 15.5$	19.5	2.34	Yes, OA inside	7, 8
021211	2.2	0.02	$R = 14.1$	0.02	$R = 14.1$	23.0	1.01	No	9, 10
030115	1.4	2.05	$R \sim 21.5$	0.01	$R > 10.0$	...	...	No	11, 12
030226	2.0	2.63	$R \sim 17.5$	0.00	$R > 11.5$	20.6	1.99	No	13, 14
030328	0.9	1.28	$R \sim 18.0$	1.28	$R \sim 18.0$	21.5	1.52	Yes, OA inside	15, 16
030329	1.2	1.56	$R = 12.6$	1.56	$R = 12.6$	16.0	0.17	Yes, OA outside	17
030429	1.9	3.48	$R = 19.7$	1.87	$R > 18.7$	21.0	2.66	Yes, OA outside	18, 19
030528	1.8	16.04	$J = 20.6$	0.04	CR > 15.8	...	...	Yes, OA inside	20, 21
030723	7.2	4.17	$R = 20.9$	0.02	CR > 18.1	21.1	...	Yes, OA inside	22, 23
040511	2.2	12.20	$J \sim 19.0$	2.18	CR > 17.2	...	...	No	24, 25
041211	2.4	...	...	0.01	$B > 11.0$	...	...	No	26
050408	1.2	2.40	$R = 20.4$	0.01	CR > 14.7	22.3	1.24	Yes, OA inside	27, 28, 29

Notes.—A list of all GRBs localized to better than 2′ radius with the SXC, where the first optical observation was performed within approximately 3 hr of the high-energy event. Here $\Delta t_{\rm SXC}$ is the time from the onset of the burst when the $\sim 2'$ SXC error circle radius was first made available, $\Delta t_{\rm OA}$ is the time after the burst when the OA was detected, and Δt_1 is the time after the GRB occurred when the first optical observation was performed. In the magnitude columns, "CR" denotes filterless observations. In the penultimate column, "RA" refers to the radio afterglow.

References.—(1) Fox et al. 2002; (2) Rhoads et al. 2002; (3) Rykoff & Smith 2002; (4) Gladders & Hall 2002; (5) Urata et al. 2003; (6) Levan et al. 2003; (7) Fox et al. 2003b; (8) Holland et al. 2003; (9) Wozniak et al. 2002; (10) Holland et al. 2004; (11) Masetti et al. 2003; (12) Castro-Tirado et al. 2003; (13) Fox et al. 2003a; (14) Klose et al. 2004; (15) Peterson & Price 2003; (16) Andersen et al. 2003; (17) Price et al. 2003; (18) Smith 2003; (19) Jakobsson et al. 2004b); (20) Uemura et al. 2003; (21) Rau et al. 2004; (22) Smith & Quimby 2003; (23) Fynbo et al. 2004; (24) Smith 2004; (25) Fox et al. 2004; (26) Sasaki et al. 2004; (27) Smith et al. 2005; (28) Misra et al. 2005; (29) Berger et al. 2005a.

expect a peak magnitude of $R = 22.3$ mag at $\Delta t \approx 20$ days. For a 2002ap-like SN the corresponding magnitude is $R = 24.8$ mag.

In Table 1, the blob magnitude at $\Delta t \approx 135$ days, when a SN and an OA contribution should be negligible, is $R = 23.76 \pm 0.15$ mag. Adding the flux from a SN at $\Delta t \approx 20$ days would result in $R \sim 22.0$ mag ($R \sim 23.4$ mag) for SN 1998bw (SN 2002ap). Since we measure the blob magnitude to be $R = 23.99 \pm 0.13$ mag and $R = 23.98 \pm 0.06$ mag at $\Delta t \approx 15$ days and $\Delta t \approx 27$ days, respectively, we do not detect the signature of a SN. This nondetection of a rising SN component may be explained by a modest host extinction, in agreement with the afterglow data (see § 4.2). A 2002ap-like SN extinguished by 1.4 mag would remain undetected, alleviating the requirement of a very subluminous SN (see also Zeh et al. 2004; Soderberg et al. 2005).

4.4. *Dark Gamma-Ray Bursts*

The need for high redshift and/or large host extinction to explain the nondetection of a large fraction of OAs is gradually disappearing. Fynbo et al. (2001) and Berger et al. (2002) demonstrated that 70%–75% of the OA searches conducted to date would have failed if the GRBs were similar to that of dim bursts like GRB 000630 and GRB 020124 in the optical band. More recently, Jakobsson et al. (2004a) used $\beta_{\rm OX}$ to introduce a new dark burst definition, resulting in a lower limit of the dark burst fraction of approximately 10%.

With the rapid availability of small GRB error circles, first attainable in 2002 August via the SXC on *HETE-2*, the stage was set for building up a small but relatively homogeneous afterglow sample. This would clarify whether deficient search strategies were indeed the reason behind the original large fraction of dark bursts. In Table 3 we have listed all GRBs localized to an SXC radius of $\lesssim 2'$, and where the first optical observation was performed within $\Delta t \approx 3$ hr.

As hinted by Lamb et al. (2004), the majority of the SXC bursts are detected in the optical, or 12/14 indicating a dark burst fraction of 10%–20%. The two bursts not detected in the optical are GRB 020819 and GRB 041211. We note that for nine bursts, the original error circle was revised a few days later, with three of those having the OA outside the original error circle. However, this does not affect the dark burst statistics significantly, although it is possible that the GRB 041211 OA was located slightly outside the error circle.

GRB 020819 has been extensively discussed in this paper. Its optical faintness is mainly due to it being intrinsically faint, i.e., with only a modest amount of extinction the extrapolation of the afterglow model from the radio to the optical is consistent with our early R-band limit. The absence of an OA for GRB 041211 is not as easily explained. This is predominantly due to the lack of multiwavelength follow-up. There is an early deep limit of $R > 21.5$ mag at $\Delta t = 3.4$ hr (Monfardini et al. 2004), but no clear conclusions can be drawn without additional X-ray or radio observations.

With the *Swift* satellite now distributing rapid and accurate positions and follow-ups with the X-Ray Telescope (XRT) and Ultraviolet/Optical Telescope (UVOT), a large homogeneous afterglow sample is finally being realized. The sample is currently rather small, with 20 bursts localized with the XRT (as of 2005 April 18). In addition, the instruments are not yet fully calibrated, implying that caution should be advised before inferring the fraction of dark bursts. The current optical/NIR afterglow recovery rate is 13/20, with at least one nondetection most likely resulting from large Galactic extinction (GRB 050117: Berger et al. 2005b). Four of the other six nondetections (GRBs 050128, 050223, 050326, and 050410) only have moderately fast and deep optical follow-ups. GRB 050219A, on the other hand, was observed with the UVOT at $\Delta t \approx 5$ minutes to a limiting magnitude of $V \sim 20.7$ (Schady et al. 2005). This burst is an excellent dark burst candidate, although the XRT results are needed to examine its consistency with the fireball model. Finally, the deep optical limit for GRB 050412 of $R > 24.9$ mag at $\Delta t = 2.3$ hr (Kosugi et al. 2005) combined with the XRT observations (Mangano et al. 2005) indicates that $\beta_{\rm OX} < 0.05$ for this burst, firmly establishing it as dark.

5. SUMMARY AND CONCLUSIONS

GRB 020819, a relatively nearby burst ($z = 0.41$), is only one of two of the 14 GRBs localized to an error radius of $\lesssim 2'$ with the SXC on board *HETE-2* that does not have a reported OA. This lends support to the recent proposition that the dark burst fraction is far lower than previously suggested, perhaps as small as 10%.

The GRB 020819 radio afterglow is superposed on a faint ($R \approx 24.0$ mag) blob, located around $3''$ from the center of a bright ($R = 19.5$ mag) barred spiral galaxy. At $z = 0.41$ this corresponds to 16 kpc. This faint blob did not show significant brightness variations over a period of $\sim$100 days, ruling it out as the OA. The probability that the assigned spiral host is a chance superposition and not physically related to the GRB, is only 0.8%.

We find that we can explain the radio afterglow without invoking large extinction to elucidate the absence of the OA. While we cannot rule out large extinction local to the GRB, it is not required. Assuming an average Galactic extinction curve ($R_V = 3.1$), the required host extinction is $A_V \approx 0.6-1.5$ mag.

We attempted a SN search by obtaining R-band data at $\Delta t \approx 15$, 21, and 27 days. We do not observe a brightening in the faint blob at these epochs. A 1998bw-like (2002ap-like) SN signature would have resulted in the blob brightening to $R \sim 22.0$ mag ($R \sim 23.4$ mag) for $z = 0.41$. We conclude that either the line of sight is extinguished ($A_V \sim 1.5$ mag would render a 2002ap-like SN undetectable), GRB 020819 is associated with a very faint SN, or it does not have a temporally coincident SN.

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REFERENCES

Andersen, M. I., Masi, G., Jensen, B. L., & Hjorth, J. 2003, GCN Circ. 1992, http://gcn.gsfc.nasa.gov/gcn/gcn3/1992.gcn3
Berger, E., Cowie, L. L., Kulkarni, S. R., Frail, D. A., Aussel, H., & Barger, A. J. 2003, ApJ, 588, 99
Berger, E., Gladders, M., & Oemler, G. 2005a, GCN Circ. 3201, http://gcn.gsfc.nasa.gov/gcn/gcn3/3201.gcn3
Berger, E., et al. 2002, ApJ, 581, 981
———. 2005b, ApJ, submitted (astro-ph/0502468)
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Björnsson, G., Gudmundsson, E. H., & Jóhannesson, G. 2004, ApJ, 615, L77
Bloom, J. S., Kulkarni, S. R., & Djorgovski, S. G. 2002a, AJ, 123, 1111
Bloom, J. S., et al. 1999, Nature, 401, 453
———. 2002b, ApJ, 572, L45
Cappellaro, E., Turatto, M., Benetti, S., Tsvetkov, D. Y., Bartunov, O. S., & Makarova, I. N. 1993, A&A, 273, 383
Castro-Tirado, A. J., et al. 2003, GCN Circ. 1826, http://gcn.gsfc.nasa.gov/gcn/gcn3/1826.gcn3
Chevalier, R. A., & Li, Z.-Y. 1999, ApJ, 520, L29
Christensen, L., Hjorth, J., & Gorosabel, J. 2004, A&A, 425, 913
Crew, G., et al. 2002, GCN Circ. 1526, http://gcn.gsfc.nasa.gov/gcn/gcn3/1526.gcn3
Foley, R. J., et al. 2003, PASP, 115, 1220
Fox, D. W., Berger, E., Moon, D., von Braun, K., & Lee, B. 2004, GCN Circ. 2597, http://gcn.gsfc.nasa.gov/gcn/gcn3/2597.gcn3
Fox, D. W., Blake, C., & Price, P. A. 2002, GCN Circ. 1470, http://gcn.gsfc.nasa.gov/gcn/gcn3/1470.gcn3
Fox, D. W., Chen, H. W., & Price, P. A. 2003a, GCN Circ. 1879, http://gcn.gsfc.nasa.gov/gcn/gcn3/1879.gcn3
Fox, D. W., et al. 2003b, Nature, 422, 284
Frail, D. A. 2005, in IAU Colloq. 192, Cosmic Explosions: On the 10th Anniversary of SN 1993J, ed. J. M. Marcaide & K. W. Weiler (New York: Springer), 451
Frail, D. A., & Berger, E. 2003, GCN Circ. 1842, http://gcn.gsfc.nasa.gov/gcn/gcn3/1842.gcn3
Fruchter, A. S., et al. 1999, ApJ, 516, 683
Fukugita, M., Shimasaku, K., & Ichikawa, T. 1995, PASP, 107, 945
Fynbo, J. P. U., et al. 2000, ApJ, 542, L89
———. 2001, A&A, 369, 373
———. 2003, A&A, 406, L63
———. 2004, ApJ, 609, 962
Galama, T. J., et al. 1998, Nature, 395, 670
———. 2003, ApJ, 587, 135
Garnavich, P. M., et al. 2003, ApJ, 582, 924
Gladders, M., & Hall, P. 2002, GCN Circ. 1513, http://gcn.gsfc.nasa.gov/gcn/gcn3/1513.gcn3
Greiner, J., et al. 2003, ApJ, 599, 1223
Groot, P. J., et al. 1998, ApJ, 493, L27
Harrison, F. A., et al. 1999, ApJ, 523, L121
Hjorth, J., et al. 2003, Nature, 423, 847
Holland, S. T., et al. 2003, AJ, 125, 2291
———. 2004, AJ, 128, 1955
Jakobsson, P., Hjorth, J., Fynbo, J. P. U., Watson, D., Pedersen, K., Björnsson, G., & Gorosabel, J. 2004a, ApJ, 617, L21
Jakobsson, P., et al. 2004b, A&A, 427, 785
Jørgensen, I. 1994, PASP, 106, 967
Klose, S., et al. 2003, ApJ, 592, 1025
———. 2004, AJ, 128, 1942
Kosugi, G., Kawai, N., Aoki, K., Hattori, T., Ohta, K., & Yamada, T. 2005, GCN Circ. 3263, http://gcn.gsfc.nasa.gov/gcn/gcn3/3263.gcn3
Lamb, D. Q., et al. 2004, NewA Rev., 48, 423
Landolt, A. U. 1992, AJ, 104, 340
Lazzati, D., Covino, S., & Ghisellini, G. 2002, MNRAS, 330, 583
Le Floc'h, E., et al. 2003, A&A, 400, 499
Levan, A., Fruchter, A., Rhoads, J., Burud, I., Rol, E., Salamanca, I., Kaper, L., & Tanvir, N. 2003, GCN Circ. 1844, http://gcn.gsfc.nasa.gov/gcn/gcn3/1844.gcn3
Mangano, V., Capalbi, M., Pagani, C., Goad, M., Kennea, J., & Burrows, D. 2005, GCN Circ. 3253, http://gcn.gsfc.nasa.gov/gcn/gcn3/3253.gcn3
Masetti, N., Palazzi, E., Pian, E., Covino, S., & Antonelli, L. A. 2003, GCN Circ. 1823, http://gcn.gsfc.nasa.gov/gcn/gcn3/041.gcn3
Misra, K., Pandey, S. B., & Kamble, A. P. 2005, GCN Circ. 3202, http://gcn.gsfc.nasa.gov/gcn/gcn3/3202.gcn3
Monfardini, A., Guidorzi, C., Mottram, C. J., & Mundell, C. 2004, GCN Circ. 2852, http://gcn.gsfc.nasa.gov/gcn/gcn3/2852.gcn3
Peterson, B. A., & Price, P. A. 2003, GCN Circ. 1974, http://gcn.gsfc.nasa.gov/gcn/gcn3/1974.gcn3
Piro, L. 2004, in ASP Conf. Ser. 312, Gamma-Ray Bursts in the Afterglow Era, ed. M. Feroci et al. (San Francisco: ASP), 149
Price, P. A., & McNaught, R. 2002, GCN Circ. 1506, http://gcn.gsfc.nasa.gov/gcn/gcn3/1506.gcn3
Price, P. A., et al. 2002a, GCN Circ. 1511, http://gcn.gsfc.nasa.gov/gcn/gcn3/1511.gcn3
———. 2002b, ApJ, 572, L51
———. 2003, Nature, 423, 844
Prochaska, J. X., et al. 2004, ApJ, 611, 200
Rau, A., et al. 2004, A&A, 427, 815
Rhoads, J., Holman, M., Kavelaars, J. J., Fruchter, A., & Levan, A. 2002, GCN Circ. 1474, http://gcn.gsfc.nasa.gov/gcn/gcn3/1474.gcn3
Rol, E., Wijers, R. A. M. J., Kouveliotou, C., Kaper, L., & Kaneko, Y. 2005, ApJ, 624, 868
Rykoff, E., & Smith, D. 2002, GCN Circ. 1480, http://gcn.gsfc.nasa.gov/gcn/gcn3/1480.gcn3

Sari, R., & Piran, T. 1999, ApJ, 517, L109
Sari, R., Piran, T., & Halpern, J. P. 1999, ApJ, 519, L17
Sari, R., Piran, T., & Narayan, R. 1998, ApJ, 497, L17
Sasaki, M., et al. 2004, GCN Circ. 2846, http://gcn.gsfc.nasa.gov/gcn/gcn3/2846.gcn3
Schady, P., et al. 2005, GCN Circ. 3039, http://gcn.gsfc.nasa.gov/gcn/gcn3/3039.gcn3
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Smith, D. A. 2003, GCN Circ. 2178, http://gcn.gsfc.nasa.gov/gcn/gcn3/2178.gcn3
———. 2004, GCN Circ. 2595, http://gcn.gsfc.nasa.gov/gcn/gcn3/2595.gcn3
Smith, D. A., & Quimby, R. 2003, GCN Circ. 2318, http://gcn.gsfc.nasa.gov/gcn/gcn3/2318.gcn3
Smith, D. A., Yost, R. A., & Rykoff, E. S. 2005, GCN Circ. 3190, http://gcn.gsfc.nasa.gov/gcn/gcn3/3190.gcn3
Soderberg, A. M., et al. 2005, ApJ, submitted (astro-ph/0502553)
Uemura, M., Ishioka, R., Kato, T., & Yamaoka, H. 2003, GCN Circ. 2252, http://gcn.gsfc.nasa.gov/gcn/gcn3/2252.gcn3
Urata, Y., Tarusawa, T., & Soyano, T. 2003, GCN Circ. 1859, http://gcn.gsfc.nasa.gov/gcn/gcn3/1859.gcn3
Vanderspek, R., et al. 2002, GCN Circ. 1508, http://gcn.gsfc.nasa.gov/gcn/gcn3/1508.gcn3
van Dokkum, P. G., & Franx, M. 1996, MNRAS, 281, 985
Villasenor, J., et al. 2004, in AIP Conf. Proc. 727, Gamma-Ray Bursts: 30 Years of Discovery, ed. E. E. Fenimore & M. Galassi (New York: AIP), 626
Wozniak, P., et al. 2002, GCN Circ. 1757, http://gcn.gsfc.nasa.gov/gcn/gcn3/1757.gcn3
Zeh, A., Klose, S., & Hartmann, D. H. 2004, ApJ, 609, 952