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CHANDRA OBSERVATIONS OF THE X-RAY ENVIRONS OF SN 1998bw/GRB 980425

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ABSTRACT

We report X-ray studies of the environs of SN 1998bw and GRB 980425 using the *Chandra X-Ray Observatory* 1281 days after the gamma-ray burst (GRB). Eight X-ray point sources were localized, three and five each in the original error boxes, S1 and S2, assigned for variable X-ray counterparts to the GRB by *BeppoSAX*. The sum of the discrete X-ray sources plus continuous emission in S2 observed by *Chandra* on day 1281 is within a factor of 1.5 of the maximum and the upper limits seen by *BeppoSAX*. We conclude that S2 is the sum of several variable sources that have not disappeared and therefore is not associated with the GRB. Within S1, clear evidence is seen for a decline of approximately a factor of 12 between day 200 and day 1281. One of the sources in S1, S1a, is coincident with the well-determined radio location of SN 1998bw and is certainly the remnant of that explosion. The nature of the other sources is also discussed. Combining our observation of the supernova with others of the GRB afterglow, a smooth X-ray light curve, spanning ~ 1400 days, is obtained by assuming that the burst and supernova were coincident at 35.6 Mpc. When this X-ray light curve is compared with those of the X-ray “afterglows” of ordinary GRBs, X-ray flashes, and ordinary supernovae, evidence emerges for at least two classes of light curves, perhaps bounding a continuum. By 3–10 yr, all these phenomena seem to converge on a common X-ray luminosity, possibly indicative of the supernova underlying them all. This convergence strengthens the conclusion that SN 1998bw and GRB 980425 took place in the same object. One possible explanation for the two classes is that a (nearly) standard GRB was observed at different angles, in which case X-ray afterglows with intermediate luminosities should eventually be discovered. Finally, we comment on the contribution of GRB afterglows to the ultraluminous X-ray source population.

Subject headings: gamma rays: bursts — supernovae: individual (SN 1998bw) —
 X-rays: individual (GRB 980425)

On-line material: color figure

1. INTRODUCTION

One of the most exciting developments in the study of gamma-ray bursts (GRBs) was the discovery, in 1998, of a GRB apparently in coincidence with a very unusual supernova of Type Ic (Galama et al. 1998). This coincidence of SN 1998bw and GRB 980425 offered compelling evidence that GRBs are indeed associated with the deaths of massive stars and that, at least in some cases, GRBs go hand in hand with stellar explosions (Woosley 1993; MacFadyen & Woosley 1999). The large energy release inferred for the supernova also suggested a novel class of explosions, called by some “hypernovae” (Paczynski 1998),

having unusual properties of energy, asymmetry, and relativistic ejecta.

However, this identification was challenged on two grounds. First, there were *two* variable X-ray sources identified with *BeppoSAX* in the initial 8'0 radius GRB error box; one was not the supernova. Second, if it were associated with the nearby supernova, GRB 980425 would be a most unusual burst, with a gamma-ray energy per solid angle roughly 4 orders of magnitude less than typical. Furthermore, the *BeppoSAX* decay of the SN 1998bw associated X-ray source was much slower than the typical GRB X-ray afterglow decay (Pian et al. 2000). Interestingly, observations (Pian et al. 2004) of the two sources in 2002 March with the *XMM-Newton* telescope revealed that the X-ray emission of the supernova-associated *BeppoSAX* error box had decreased at a faster pace than expected by a simple extrapolation of the earlier measurements. Moreover, the second *XMM* source was found to consist of a number of faint pointlike sources, whose integrated emission was consistent with the average brightness measured with *BeppoSAX* (Pian et al. 2000).

Additional strong support for the GRB-supernova association came from the recent spectroscopic detection (Hjorth et al. 2003; Stanek et al. 2003) of a supernova (SN 2003dh) in the optical light curve of GRB 030329. In this case, the supernova detection was obscured by the extreme optical brightness of the GRB afterglow. This may be related to the fact that GRB 030329 was a nearly normal GRB, while GRB 980425 was very subluminal.

Here we report the results of a study of the environs of SN 1998bw and GRB 980425 using the *Chandra X-Ray*

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Observatory 1281 days after the GRB. This study had several goals. First, given the intervening 3 years, has the evidence strengthened for the GRB-supernova association? We believe that it has (§ 4.1). Second, how does the X-ray light curve of GRB 980425, measured across 1400 days, compare with those of other GRBs and with other kinds of high-energy transients—in particular, X-ray flashes (XRFs; Heise 2003) and supernovae? What does the comparison tell us about the nature and origin of GRBs? We find that it provides evidence for a common theme underlying all these events: a powerful asymmetric supernova with relativistic ejecta along its polar axes and an observable event that varies depending on the viewer’s polar angle (§§ 4 and 5).

Finally, we are interested in the environs of SN 1998bw. Aside from the one supernova, does this region show evidence for unusual stellar activity as might characterize a vigorously star-forming region (§ 3.1)? SN 1998bw offers the best opportunity to study a GRB site up close, and one should take every advantage of that.

2. PROMPT OBSERVATIONS OF GRB 980425 AND SN 1998bw

GRB 980425 triggered *BATSE* on board NASA’s *Compton Gamma-Ray Observatory* on 1998 April 25, 21:49:09 UT; the event was simultaneously detected by the *BeppoSAX* Gamma-Ray Burst Monitor (GRBM) and Wide Field Camera (WFC). The burst consisted of a single peak of ~ 23 s duration, with peak flux and fluence (24–1820 keV) of $(3.0 \pm 0.3) \times 10^{-7}$ ergs $\text{cm}^{-2} \text{s}^{-1}$ and $(4.4 \pm 0.4) \times 10^{-6}$ ergs cm^{-2} , respectively. Galama et al. (1998) observed the WFC 8’0 error box with the New Technology Telescope at the European Southern Observatory (ESO) on April 28.4 and May 1.3 UT, and in the error box of GRB 980425 they found supernova SN 1998bw, located in an H II region in a spiral arm of the face-on barred spiral galaxy ESO 184-G82, at $z = 0.0085$, corresponding to a distance of 38.5 Mpc. (Galama et al. [1998] assumed a Hubble constant $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, but in the following we use $H_0 = 72 \pm 8.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$, as measured by Freedman et al. [2003], placing SN 1998bw at 35.6 Mpc.)

On 1998 April 26–28, 10 hr after the GRB, the *BeppoSAX* Narrow Field Instruments (NFI) observed (Pian et al. 2000) the WFC error box and revealed two previously unknown, weak X-ray sources, 1SAX J1935.0–5248 (S1) and 1SAX J1935.3–5252 (S2), with an uncertainty radius of 1’5 each. S1 included SN 1998bw, but S2 was 4’5 away. Both sources were observed two more times with the NFI, resulting, in the case of S2, in two detections and two upper limits. In contrast, during the 6 month interval spanned by all NFI observations, the flux F of S1 followed a power-law temporal decay (Pian et al. 2000):

$$F_{2-10 \text{ keV}} = (4.3 \pm 0.5) \times 10^{-13} \left(\frac{t}{1 \text{ day}} \right)^{-0.2} \text{ ergs cm}^{-2} \text{ s}^{-1},$$

a much flatter trend than the one observed for other GRB X-ray afterglows, but a decaying trend nevertheless.

At 35.6 Mpc the apparent isotropic energy of GRB 980425 (7×10^{47} ergs) was about 4 orders of magnitude smaller than that of “normal” GRBs (Bloom et al. 2003). Moreover, independent of its connection with a GRB, SN 1998bw was extraordinary in many ways. Its light curve resembled a Type Ia supernova in brilliance, but the spectrum was more like Type Ic (H, He, and Si lines were absent, but the spectrum

was peculiar even for Type Ic). Thus, the two phenomena together presented a very interesting scientific puzzle whose solution required the combined superb resolution of the *Hubble Space Telescope* (HST) and *Chandra*.

3. CHANDRA OBSERVATIONS AT DAY 1281

Chandra observed S1 and S2 on 2001 October 27, for a total time on source of 47.7 ks. S1 fell completely on ACIS-S3 (a back-illuminated CCD), and S2 only partially, with most of the error region falling on ACIS-S2 (a front-illuminated CCD), both operating in time-exposure mode. The data were processed using the CIAO (ver. 3.0.1)¹⁰ and CALDB (ver. 2.34)¹¹ software. More specifically, we used the CIAO tool *acis-process-events* to ensure that the latest gain corrections were applied (those corresponding to our observation date). Furthermore, we removed the standard pixel randomization, applied charge transfer inefficiency corrections, filtered the data to include events with *ASCA* grades of 0, 2, 3, 4, and 6, and applied standard good time intervals. We corrected the systematic offset in the aspect using the *fix-offset* thread;¹² this resulted in an offset of $\delta \text{R.A.} = 0'16$ and $\delta \text{decl.} = 0'43$. To improve the ACIS-S3 spatial resolution, we used the method described by Mori et al. (2001) and Tsunemi et al. (2001) to adjust the event locations. These studies conclude that by defining the event location on a pixel as a function of the event grade (rather than placing the event at the pixel center), one can achieve $\sim 10\%$ improvements in spatial resolution. During our observation the X-ray background increased by $\sim 50\%$ with variations on timescales of a few kiloseconds. Since the point-source emission is not significantly masked by such slow background variations, we chose to include all the data in our analysis to preserve our (limited) source counts.

3.1. S1 and S2: Source Identification, Locations, and Energetics

We used the source-finding method originally described in Swartz et al. (2002), accepting as detections all sources with a minimum signal-to-noise ratio (S/N) of 2.6. For source detection purposes we searched images consisting of data between 0.3 and 8.0 keV to avoid the ACIS high-energy background. We discuss below the sources within the 1’5 radius (1 σ) NFI error circles of S1 and S2 only.

3.1.1. S2

S2 was resolved into five sources (S2a, b, c, d, and e; Fig. 1c, Table 1). Given the very limited count number per source, we combined four of them into one spectral fit with a power-law function and a hydrogen column density $N_{\text{H}} = 3.95 \times 10^{20} \text{ cm}^{-2}$ (corresponding to the Galactic absorption in the line of sight to GRB 980425; Schlegel et al. 1998). Here we assume a spectral similarity between these sources to mitigate the difficulty of fitting individual spectra of very few counts each. This order of magnitude approximation is acceptable within our source statistics (see also Fig. 2, in which rudimentary count spectra are presented for S1a, b, and c and S2c and e). However, one source (S2d) fell into the gap between the ACIS CCDs S2 and S3, and its total counts had to be adjusted, taking into account the reduced gap exposure time. Using the spectral index of -1 from the fit, we applied a conversion factor of

¹⁰ See <http://cxc.harvard.edu/ciao>.

¹¹ See <http://asc.harvard.edu/caldb>.

¹² See <http://cxc.harvard.edu/cal/ASPECT>.

FIG. 1.—(a) Digitized Sky Survey image of the area around GRB 980425. The outer (partial) circle represents the $8'0''$ error region for GRB 980425 from the *BeppoSAX* WFC. The complete circles represent the $1'5''$ *BeppoSAX* NFI S1 and S2 error regions. The dashed circle (radius of $15''$) within S1 identifies the area covered by the GRB 980425 host galaxy ESO 184-G82. (b) *Chandra* image of S1. The boxed region containing S1ab (lower left) and S1c (upper right) is shown in (d). (c) *Chandra* image of S2. Almost the entire error region (over 97%) was covered by the *Chandra* CCDs S2 and S3. Source S2d falls into the gap between these two CCDs. (d) *Chandra* blow-up of the square box in (b). The dashed circle (radius of $15''$) indicates the host galaxy area (also identified in [a]). A close-up view of the solid box shown here is seen in (e). (e) *Chandra* blow-up of the square box in (d). Sources S1a and S1b are clearly resolved. S1a is the source to the south and coincides with the established radio location of SN 1998bw. The two circles represent the 1σ error regions for these sources with $r = 0'3$ derived with comparative astrometry. (f) *HST* STIS image of (e) taken in the 50 CCD/Clear mode (no filter). The circles are the *Chandra* error circles from (e).

1.89×10^{-11} ergs $\text{cm}^{-2} \text{s}^{-1}$ (0.3–10.0 keV) per count s^{-1} (0.3–8.0 keV) to the S2d counts and finally estimated the total (combined) flux in S2 (0.3–10 keV) to be $3.0(3) \times 10^{-14}$ ergs $\text{cm}^{-2} \text{s}^{-1}$ (here and in Table 1 the numbers in parentheses correspond to the 1σ errors in the last digit).

The *BeppoSAX* flux for S2 was, however, calculated using a $3'$ extraction radius to account for the extreme faintness of the detection within a $1'5''$ radius (which was at the level of the NFI confusion limit) and, at the same time, to avoid contamination from S1 (Pian et al. 2000). Only $\sim 60\%$ of this larger error circle is covered with *Chandra*. Using the same source-finding algorithm criterion described above, we found a total of 18 sources within the enlarged area, with a total flux of $S2(3') = 1.6 \times 10^{-13}$ ergs $\text{cm}^{-2} \text{s}^{-1}$. This is roughly the flux to be compared with the *BeppoSAX* S2 value at day 1. Subsequently, we recalculated the total *BeppoSAX* flux within S2 at day 1, using the same spectral function derived with *Chandra* and a $1'5''$ radius, and found it to be 4×10^{-13} ergs $\text{cm}^{-2} \text{s}^{-1}$ (with $< 2\sigma$ significance). Taking into account the partial coverage with *Chandra* of the NFI error circle of S2, we estimate that the day 1281 *Chandra* flux value is within a

factor of 1.5 of the 3σ detection limit of *BeppoSAX*, indicating that at best there was no significant variation of the sources within S2 over the last 3.5 yr. This result is consistent with the *XMM* observations of S2 (Pian et al. 2004). We further discuss the evolution of the light curve of S2 in § 4.1.

3.1.2. S1

We initially identified two sources $36''$ apart within the S1 ($1'5''$) error region,¹³ one of which coincided with the location of SN 1998bw. However, further inspection of the latter resolved this source into two, with a radial separation of $\sim 1'5''$ (Fig. 1b). We fitted these sources simultaneously with two two-dimensional circular Gaussians to better estimate their centroids and found that they are both consistent with point sources. Hereafter we designate the X-ray sources detected

¹³ Here we are only considering the area corresponding to the NFI half-power radius of $1'5''$, as most of the *BeppoSAX* signal for S1 at day 1 was within this area (Pian et al. 2000). An enlarged radius region ($3'$) for S1 results in a total flux of 2.7×10^{-13} ergs $\text{cm}^{-2} \text{s}^{-1}$, almost half the *BeppoSAX* value at day 1.

TABLE 1
Chandra SOURCES WITHIN S1 AND S2; DAY 1281

ID	R.A. (J2000.0)	Decl. (J2000.0)	Counts ^a	S/N	Index ^b	Flux ^c (ergs cm ⁻² s ⁻¹)	Luminosity ^{c,d} (ergs s ⁻¹)
S1a.....	19 35 3.31	-52 50 44.8	24	4.53	1.0(3)	$8(2) \times 10^{-15}$	1.2×10^{39}
S1b.....	19 35 3.23	-52 50 43.4	52	6.47	1.6(2)	$9(1) \times 10^{-15}$	1.4×10^{39}
S1b ^{corr}	...	...	40	...	1.7(3)	$1.4(2) \times 10^{-14}$	2.2×10^{39}
S1c.....	19 35 0.56	-52 50 21.2	27	4.69	0.5(3)	$1.2(2) \times 10^{-14}$	...
S2a ^e	19 35 25.75	-52 54 19.0	10	2.75	...	$4(1) \times 10^{-15}$	...
S2b ^e	19 35 25.22	-52 54 21.2	7	2.66	...	$3(1) \times 10^{-15}$	...
S2c.....	19 35 24.65	-52 54 40.7	22	4.46	1.7(4)	$5(1) \times 10^{-15}$	...
S2d ^f	19 35 23.15	-52 53 5.6	9	2.82	...	$8(3) \times 10^{-15}$	...
S2e.....	19 35 14.03	-52 53 51.9	23	4.19	0.7(3)	$1.0(2) \times 10^{-14}$	...

NOTES.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Here and in the text, the numbers in parentheses correspond to the 1σ errors in the last digit.

^a Between 0.3 and 8.0 keV and with an extraction radius of $0''.74$.

^b For an energy spectrum of $\propto E^{-\gamma}$.

^c Between 0.3 and 10.0 keV.

^d Assuming the source is in ESO 184-G82 at 35.6 Mpc.

^e Fluxes for sources with less than 20 counts are derived using a power-law index of -1.0 and a conversion factor of 1.89×10^{-11} ergs cm⁻² s⁻¹ (0.3–10.0 keV) per 1 count s⁻¹ (0.3–8.0 keV).

^f Source flux corrected for decreased exposure.

FIG. 2.—Light curves (left; binned in 3000 s wide bins) and spectra (right; binned in 0.232 keV wide bins) of the five sources with more than 20 counts total within S1 and S2 collected with *Chandra* (0.3–10.0 keV). Note that source S1b is highly variable during the 50 ks observation. All other sources are either too faint to determine any variability or consistent with a constant persistent emission.

within the S1 error region as S1a (corresponding to SN 1998bw), S1b, and S1c. We have fitted a power law to each unbinned, non-background-subtracted source spectrum, assuming the same N_H as for S2. Our fit parameters are derived using the C -statistic (Cash 1979), appropriate for low-count data (Table 1).

Furthermore, we reanalyzed all archival *HST* and ESO Very Large Telescope (VLT) observations of ESO 184-G82, the host galaxy of SN 1998bw, concentrating on the immediate environment of the source initially identified as the supernova by Fynbo et al. (2000) and later confirmed by Sollerman et al. (2002). The small field of view of the *HST* STIS ($\sim 50''$) contains only the sources S1a and S1b. In order to obtain accurate astrometry, we therefore registered both *Chandra* and *HST* images independently to an R -band observation obtained at the VLT on 1999 April 18. The 3.4×3.4 field of the VLT image contained three additional X-ray sources with apparent optical counterparts, which we used to align the two fields. Finally, we aligned the *HST* and VLT images using eight nonsaturated point sources present in each image (both alignments were performed using IRAF and the tasks *geomap* and *geoxytran*). We were then able to project the relative position of S1a and S1b onto the *HST* field with a positional accuracy of $\sim 0.3''$. This is shown schematically in Figures 1e and 1f, in which we zoom into the region around S1a and S1b for both *Chandra* and *HST* data. We clearly see in the *HST* image the optical counterpart to SN 1998bw. We also find a possible optical counterpart within the ~ 0.3 *Chandra* error circle (1σ radius) of S1b, with a preliminary V magnitude of ~ 27.0 . A. Levan et al. (2004, in preparation) present a detailed study of this source together with four transient sources within a radius of $6''$ of SN 1998bw, as well as narrow-field spectroscopy of the SN 1998bw environment. A counterpart search for the other six sources in S1 and S2 in all available catalog data¹⁴ failed to identify any known objects at their positions.

From Table 1 we notice that the X-ray luminosities of S1a and S1b marginally exceed the ultraluminous X-ray source (ULX) threshold luminosity of $L = 1 \times 10^{39}$ ergs s⁻¹ (Fabbiano 1989).¹⁵ Furthermore, inspection of the S1b light curve in Figure 2 reveals that the source was “on” during the first ~ 20 ks of our *Chandra* observation, remained “off” for the following ~ 28 ks, and possibly turned on again during the last 2 ks of the observation. We proceeded in correcting our estimate of the source flux (see Table 1; S1b^{corr}), taking into account the actual source-on time of 22.2 ks, which resulted in a luminosity of 2.2×10^{39} ergs s⁻¹. Counting the GRB-supernova source also as a ULX, we then have two of these sources in ESO 184-G82. What is the probability that S1b resides in ESO 184-G82, how common are ULXs in galaxies, and what is the nature of S1b, this ultraluminous X-ray transient?

To address the first question, we use the $\log N$ - $\log S$ relation by Giacconi et al. (2001) for hard X-ray sources: $N(>S) = 1200(S/2 \times 10^{-15})^{-1 \pm 0.2}$ sources deg⁻² (the one for the soft sources is smaller, so we use this as a conservative upper limit). Substituting for $S = 1.4 \times 10^{-14}$ ergs cm⁻² s⁻¹, we find $N(>S) = 170$ sources deg⁻². Correspondingly, we expect 0.004 sources within a radius of $10''$. We conclude that S1b is

most likely associated with the spiral arm of ESO 184-G82 and is not a background source.

There are two extensive studies of ULX populations in normal galaxies (Roberts & Warwick 2000; Humphrey et al. 2003) based on data from *ROSAT* and *Chandra*, respectively. While both studies find substantial evidence for a correlation between ULX count number and star-forming mass, the *ROSAT* survey tends to underestimate their count numbers by a factor of 5–10 with respect to *Chandra*. We have therefore used the *ROSAT* luminosity distribution $dN/dL_{38} = (1.0 \pm 0.2)L_{38}^{-1.8}$, normalized to a B -band luminosity of $10^{10} L_{\odot}$, to calculate the expected number of ULXs in ESO 184-G82, multiplied by a factor of 10 as indicated by the *Chandra* survey. We derive a total corrected expected number of 0.28 ULXs in ESO 184-G82, a factor of ~ 7 less than the actual observed number of 2. We conclude that if S1a and S1b are both in ESO 184-G82, there is a somewhat unusual concentration of ULXs in this galaxy. Finally, ESO 184-G82 is one of five members of a galaxy group. In the *Chandra* data, which cover all members, we do not detect any other X-ray sources from this group. This practically means that, assuming all members are at the distance of ESO 184-G82, we detect only two ULXs from the whole group (one of which is a GRB/supernova afterglow), both within a radius of $6''$. We discuss the results of narrow-band photometry of ESO 184-G82 together with the properties of other unusual transients found in the *HST* data in the SN 1998bw environment in detail in A. Levan et al. (2004, in preparation).

To test S1b for variability, we extracted the source light curve in 1000 s bins and performed a Kolmogorov-Smirnov test against a constant flux distribution; this is the preferred method for the low number of counts (< 100) that are seen from the source. We derive $P_{KS} = 0.05$ (where P_{KS} is the probability that the source is constant); thus, S1b is consistent with being variable at the 95% confidence level. The transient nature and the energetics of S1b indicate a possible microquasar similar to, e.g., GRO J1915+105 in our own Galaxy (Mirabel & Rodríguez 1994; Greiner et al. 1996). This superluminal source exhibits transient behavior in a wide variety of timescales and intensities and has an apparent (isotropic) X-ray luminosity of $\sim 7 \times 10^{39}$ ergs s⁻¹, well above its Eddington limit (Greiner et al. 2001). Fabbiano et al. (2003) have found in a study with *Chandra* of the ULX sources in the Antennae galaxies that seven out of the nine ULXs are time-variable, most likely accreting compact X-ray binaries. Interestingly, the average co-added spectrum of the Ant ULXs resembles that of Galactic microquasars (Zezas et al. 2002). Very recently, Soderberg et al. (2004) reported the detection with the Australia Telescope Compact Array of a weak radio source (209 μ Jy at 2368 MHz), possibly the radio counterpart of S1b; if the identification is confirmed, S1b would be the second ever ULX with a radio detection Kaaret et al. 2003. Taking into account its X-ray properties and its putative optical and radio counterparts, we conclude that, most likely, S1b is a microquasar in ESO 184-G82. However, more multiwavelength observations are necessary to bring out the nature of this source.

4. SYSTEMATICS OF THE X-RAY LIGHT CURVES OF HIGH-ENERGY TRANSIENTS

Figure 3 shows, on a common scale, all GRB afterglows with measurements covering several tens of days. There are, unfortunately, only a few curves, because such measurements can only be made on GRBs that are relatively nearby, but their

¹⁴ See <http://heasarc.gsfc.nasa.gov/db-perl/W3Browse/w3browse.pl>.

¹⁵ Here we are not discussing the nature of S1c, as there is no clear evidence for the association of this source with ESO 184-G82.

FIG. 3.—Compilation of GRB, XRF, and Type I and II supernova X-ray light curves (0.3–10 keV) presented as (isotropic) luminosity distances using a cosmology with $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, and $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The XRF luminosities are calculated assuming two redshifts, $z = 1$ (solid lines) and 0.251 (dashed lines). The solid long line corresponds to a temporal decay of $10^{46} t_{\text{days}}^{-1.69}$, discussed in the text. [See the electronic edition of the *Journal* for a color version of this figure.]

light curves should be illustrative. For GRB 030329 we used data points from both the *Rossi X-Ray Timing Explorer* and *XMM* reported by Tiengo et al. (2003, 2004). The original four points of GRB 980425 were reported by Pian et al. (2000); the fifth point is the *Chandra* observation of this paper; the sixth point is the *XMM* measurement taken on 2002 March 28, originally reported by Pian et al. (2004). Unfortunately, *XMM* cannot resolve S1a and S1b, so the luminosity value on Figure 3 includes both sources. We reanalyzed the *XMM* data (for a description of the data reduction and processing, see Pian et al. 2004), excluding periods of time when the background was very high (flaring), and measured a net count rate of $7.5 \times 10^{-3} \text{ counts s}^{-1}$ (0.3–10 keV) during an exposure time of $\sim 10 \text{ ks}$, within a $30''$ extraction radius. We grouped the data into energy bins with at least 15 counts each, calculated and subtracted the background, averaging four regions (each of $30''$ radius) selected in the vicinity of S1a+S1b, and finally fitted a power-law function using the same hydrogen column density as with the *Chandra* and *BeppoSAX* data. The best-fit spectral index is $-2.4(6)$, with a $\chi^2 = 13.9$ for 12 degrees of freedom, and the corresponding (unabsorbed) flux and luminosity are $2.1 \times 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}$ and $3.1 \times 10^{39} \text{ ergs s}^{-1}$, respectively. These values are very similar to the sum^{16} of the *Chandra* flux and luminosity values for S1a and S1b but differ from the originally reported values in Pian et al. (2004), who assume a fixed spectral index of -1 for the power-law fit. We let the index be free in our fit to account for the contribution from two sources of (significantly) different intensities and spectra.

For GRBs 021004, 010222, 000926, and 970228, we used data from Sako & Harrison (2002a, 2002b), Björnsson et al. (2002), Harrison et al. (2001), and Costa et al. (1997), respectively. We reanalyzed all data, calculated the fluxes in the same energy interval (0.3–10 keV), and then converted them into (equivalent isotropic) luminosities using a cosmology of $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, and $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$ to

eliminate the distance dependence. As has been noted many times, GRB 980425 and its early afterglow fall orders of magnitude below the ordinary GRBs.

We then compared these curves with those of both supernovae of all types and XRFs. We collected, reanalyzed, and converted flux data to luminosities as described above for the Type IIb SN 1993J (Uno et al. 2002; Swartz et al. 2002), the Type Ic SNe 1994I and 2002ap (Immler et al. 2002; Sutaria et al. 2003; Soria et al. 2004), and the Type II SNe 1998S and 1999em (Pooley et al. 2002). Each source is indicated with a different symbol in Figure 3. Finally, we added the three XRF afterglow light curves available (011030, 020427, and 030723; Bloom et al. 2003; Butler et al. 2003), assuming a redshift of $z = 1$ for each of them (there are no redshift measurements for any of these sources). The slopes of the XRF afterglows agree well with those of typical GRBs, and their luminosities are comparable for the distances assumed. Recently, Soderberg et al. (2003a) have reported the counterpart identification of XRF 020903 at a redshift $z = 0.251$. To reflect this lower distance scale for XRFs, we plot on Figure 3 another set of light curves (dashed lines) corresponding to the luminosities that all XRFs mentioned above would have when placed at a distance of $z = 0.251$. They still fall well within the typical GRB range; thus, XRFs would have to be extremely nearby for their X-ray light curves to be distinct from the generic GRB X-ray afterglow.

The resulting plot is striking in several ways. Despite the huge disparity in initial appearance, there are indications of a common convergence of all classes of phenomena plotted—GRBs, GRB 980425, XRFs, and the most energetic supernovae—to a common resting place, $L \sim 10^{39} - 10^{40} \text{ ergs s}^{-1}$ about 3–10 yr after the explosive event. GRB 980425, being the closest by far of any GRB ever studied, has the virtue of being followed all the way to the “burial ground,” but simple logarithmic extrapolations of the GRB and XRF light curves place them squarely in this region as well. As the collapsar model has predicted (MacFadyen & Woosley 1999) and observations of SN 2003dh/GRB 030329 have unambiguously confirmed for one case (Hjorth et al. 2003; Stanek et al. 2003), an energetic supernova is expected to underly all GRBs of the long, soft variety (Kouveliotou et al. 1993). Zhang et al. (2004) have also predicted that a similar supernova will underly all XRFs.

We proceed now to a wider GRB X-ray afterglow comparison with those plotted on Figure 3. We have often observed GRB afterglows with temporal decays that cannot be described by a single power law. Rather, these afterglows initially decay as t^{-1} or a bit steeper, and at later times the decay index becomes approximately -2 (Pian et al. 2001; Harrison et al. 2001; Piro et al. 2001). This steepening is attributed to the fact that the ultrarelativistic outflow is initially collimated within some angle θ (typically thought to be of the order of 10° ; Frail et al. 2001; see also van Paradijs et al. 2000 and references therein). The transition to a steeper power law marks the time when the outflow begins to expand laterally, which occurs around the time when $\theta \sim 1/\Gamma$, where Γ is the Lorentz factor of the blast wave. Typically, the “break time” when this happens is around 0.3–3 days after the burst, but a few cases have much later breaks, if any (e.g., GRB 970508, 000418; Frail et al. 2001). If this is also true for the X-ray afterglows shown in Figure 3, then they should be extrapolated to later times with a steeper power law than the average of the data shown. In that case, they should reach the luminosity level of supernovae sooner, and after that evolve like

¹⁶ Here we assumed the uncorrected (average) flux value for S1b, as we cannot determine the source state from the *XMM* data alone. (However, we find a 91% probability that the summed source light curve is variable.)

the supernovae, because the blast wave will have become nonrelativistic. Thereafter, the system may simply evolve like an X-ray supernova with an energy that has been augmented with that of the initially relativistic blast wave. However, it is tantalizing that a few systems, e.g., GRB 030329, do not yet show such a steep decay, even at 30–40 days, possibly indicating that other mechanisms than the standard collimated afterglow contribute to the emission. For example, it has been proposed that the outflows of GRBs are structured (e.g., Mészáros et al. 1998; Rossi et al. 2002; Ramirez-Ruiz et al. 2002), i.e., that they eject material with ever lower Lorentz factors at ever larger angles from the jet axis. Numerical simulations of collapsars have shown that this is a natural physical occurrence (MacFadyen & Woosley 1999; Zhang et al. 2004). If the energy in these wings is sufficiently large, this slower moving material affects the afterglow at late times, making it decay more slowly. In this context, it is interesting to note that in GRB 030329 there is evidence for two jet breaks, one at 0.5 days and one at about 1 week (Berger et al. 2003b), from radio to X-ray data. Moreover, Westerbork Synthesis Radio Telescope radio data at 1.4–5 GHz indicate that there is probably an even wider outflow of yet slower material (E. Rol et al. 2004, in preparation). It is not yet certain, however, that this material produces enough X-ray emission to explain the slow, late decays.

From Figure 3 alone, it is not clear whether ordinary GRBs and GRB 980425 are two distinct classes of events with different X-ray light curves, or if they form the boundaries of a continuum of high-energy transients that will eventually fill in the entire left side of the figure. A simple theoretical interpretation discussed in § 5 favors a continuum of events in which the early luminosity is sensitive to the angle at which the event is observed. This suggests that the low X-ray luminosity (Rodríguez-Pascual et al. 2003; Watson et al. 2004; Fox et al. 2004) of the recently discovered GRB 031203 may have also been due to its having been viewed substantially off-axis.

4.1. The X-Ray Light Curve of Sources S1 and S2

Figure 4 summarizes the X-ray observations of sources S1 and S2. The first four data points (or upper limits) up to day 200 are from *BeppoSAX* (Pian et al. 2000) and do not resolve individual sources within S1 and S2; our *Chandra* observations on day 1281 do resolve the sources. We consider two hypotheses: (1) that SN 1998bw and GRB 980425 were the same event, both happening within S1, and (2) that GRB 980425 occurred within the error box of S2 at a cosmological distance and was thus a more ordinary GRB. Hence, the S2 observations are plotted at distance $z = 1.34$, such that the afterglow luminosity on day 1 is comparable to ordinary GRBs (see also § 4). The S1 observations are plotted with an assumed distance of 35.6 Mpc, the distance to the supernova. The subtraction of the known fluxes of sources S1b and S1c on day 1281 from the four *BeppoSAX* points reduces their values by $\sim 4\%$, which is less than the size of the symbols used in the plot. We chose instead to plot the sum of all three S1 sources in Figure 4 ($S1_{\text{sum}}$) to indicate the “expected” flux from extrapolation of the *BeppoSAX* X-ray light curve of S1 and compare it with the flux of the S1a (the SN 1998bw) point only.

In contrast to the curve for S1 or ordinary GRBs (Fig. 3), the curve for S2 shows random variability and is nearly flat [assuming $S(3')$ for the *Chandra* flux of S2 on day 1281]. It is consistent with a collection of variable X-ray sources, probably

FIG. 4.—X-ray light curves of sources S1 and S2. The upper curve gives the two *BeppoSAX* observations and upper limits for the error box of S2 during the first 200 days after the GRB trigger. The last points (day 1281) on that curve are the sum ($S2_{\text{sum}}$) of all point sources observed with *Chandra* and the sum [$S2(3')$] of all sources observed with *Chandra* within an error circle of $3'$ radius. A distance of $z = 1.343$ has been assumed for all S2 points (see text). The arrow on day 1281 reflects the *Chandra* detection limit of a source placed at $z = 1.343$ or less. The lower curve is the light curve of source S1 assuming a distance equal to that of ESO 184-G82 (35.6 Mpc). The first four points are the *BeppoSAX* observations; the fifth (upper) point at day 1281 is the sum of all S1 *Chandra* sources ($S1_{\text{sum}}$). The point below $S1_{\text{sum}}$ is the SN 1998bw luminosity after we subtract the flux contribution of sources S1b and S1c from $S1_{\text{sum}}$.

distant active galactic nuclei, whose sum sometimes exceeds and at other times falls below the *BeppoSAX* threshold. The total flux of the *Chandra* observations of the sources within the larger ($3'$ radius) error circle of S2 is within a factor of 1.5 of the brightest flux ever detected by *BeppoSAX* for S2 (day 1) and the two upper limits given by *BeppoSAX* on days 2 and 200. If the GRB afterglow occurred within S2 either it declined more rapidly than any other afterglow ever studied before, in which case the observations of S2 offer no supporting evidence for the connection, or it created a most unusual afterglow that has not declined, in over 3 yr. Moreover, the afterglow on day 1281 would have a luminosity orders of magnitude greater than other GRBs after day 50 (Fig. 3). The simplest conclusion is that S2 did not contain GRB 980425 and that the *BeppoSAX* detection was a collection of variable background sources.

The light curve of S1, on the other hand, shows a gentle decline to day 200, followed by a rapid fading by a factor of about 12 to 1.1×10^{39} ergs s^{-1} by day 1281 (here we compare the *BeppoSAX* value at day 1 with $S1_{\text{sum}}$). This last data point is consistent with the light curves of other particularly luminous supernovae, e.g., the Type II SN 1993J, that may have had high mass loss rates, but one must take care, because SN 1998bw was a Type Ic supernova, which presumably occurred in a Wolf-Rayet star. Such stars are known to have a high wind velocity, and hence a low circumstellar density. Bregman et al. (2003) have recently discussed the X-ray emission of young supernovae and found that most have an X-ray luminosity in the 0.5–2 keV energy band less than 2×10^{39} ergs s^{-1} . They do point out exceptional cases—SN 1978K, SN 1996J, SN 1998Z, SN 1995N, and SN 1998S—that have X-ray luminosities from $10^{39.5}$ to 10^{41} ergs s^{-1} , even a decade after the event, but these were all Type II. Given the exceptionally large kinetic energy inferred for SN 1998bw (Iwamoto et al. 1998; Woosley et al. 1999), perhaps it is not surprising that its

luminosity after 3 yr should place it, e.g., about an order of magnitude above common Type Ic supernovae such as SN 1994I.

The simple hypothesis we want to explore in § 5 is that the brilliant emission of S1a during the first days was the X-ray afterglow of the relativistic ejecta that made GRB 980425, ejecta that were moving in our direction. By day 1281, however, we were seeing the energetic, but not especially relativistic, ejecta of SN 1998bw colliding with the presupernova mass loss of its progenitor star. Along the way, the X-ray light curve may have been augmented by the emission of a more energetic central jet that was not beamed in our direction but became visible as it slowed.

5. THEORETICAL INTERPRETATION

The X-ray afterglow emission of ordinary GRBs is generally attributed to synchrotron emission from shocks as the blast encounters the interstellar or circumstellar medium. Some useful scaling relations for blast waves, in which each particle emits a fixed fraction ϵ of the energy it gains in the shock, have been given by Cohen et al. (1998):

$$L(t) \propto t^{-[(m-3)/(m+1)]-1}, \quad (1)$$

with

$$m = \frac{\epsilon^2 + 14\epsilon + 9}{3 - \epsilon}. \quad (2)$$

Fundamentally, $0 < \epsilon < 1$ and $3 < m < 12$, so that $L \propto t^{-1}$ to $t^{-22/13} = t^{-1.69}$. This expression is for constant density. Chevalier & Li (2000) also give expressions for the power-law scaling of afterglow light curves and find, for a medium with $\rho \propto r^{-2}$,

$$L(t) \propto t^{-\alpha}, \quad (3)$$

with $\alpha = 1.75$ – 2.17 for radiative blast waves and 1.38 – 1.75 for adiabatic blast waves if the index of the electron power distribution, p , is between 2.5 and 3.0. The curve $L = 10^{46} t^{-1.69}$ ergs s⁻¹ is plotted in Figure 3 and provides a reasonable description of the early X-ray afterglow light curve (when most of the energy is emitted at these frequencies). At observer times longer than 1 week, the blast wave would, however, be decelerated to a moderate Lorentz factor, irrespective of the initial value. The beaming and aberration effects are thereafter less extreme. If the outflow is beamed, a decline in the light curve is expected at the time when the inverse of the bulk Lorentz factor equals the opening angle of the outflow (Rhoads 1997). If the critical Lorentz factor is less than 3 or so (i.e., the opening angle exceeds 20°), such a transition might be masked by the transition from ultra-relativistic to mildly relativistic flow, so quite generically it would be difficult to limit the late-time afterglow opening angle in this way if it exceeded 20°. For reasonable conditions, then, the power-law declines of both XRFs and luminous GRBs, given in Figure 3, are what might be expected from very relativistic ejecta slowing in either a constant-density medium or a circumstellar wind.

However, the nearly flat X-ray light curve of SN 1998bw during the first few hundred days needs a different explanation. GRB 980425, or at least that portion directed at us, was very weak. Two possibilities are frequently considered: First, that GRB 980425 was an “ordinary” (or somewhat subluminal)

GRB observed off-axis. This has been suggested many times (e.g., Woosley et al. 1999; Nakamura 1999; Granot et al. 2002; Yamazaki et al. 2003; Zhang et al. 2004) with different underlying assumptions regarding the angular distribution of the ejecta. Nakamura (1999) assumes that the jet has sharp edges and that the peripheral emission comes from scattering. Woosley et al. (1999) assume that there is a distribution of ejecta energies and Lorentz factors and that, during the burst, we see only the low-energy wing moving toward us. The other possibility is that GRB 980425 was deficient in energetic gamma rays at all angles. This is not incompatible with the fact that it may have ejected 3×10^{50} ergs of mildly relativistic ($\Gamma > 2$) material (Li & Chevalier 1999); it concerns only the very relativistic ejecta, $\Gamma > 200$, thought to be responsible for harder, brighter GRBs.

The light curve of the X-ray afterglow alone probably does not distinguish between these two possibilities. For example, Waxman (2004a, 2004b) points out that the ejection of mildly relativistic matter ($\beta \sim 0.8$; $E \sim 10^{49.7}$ ergs) in a spherical explosion would give a nearly flat light curve for the first 100 days, followed by a decay as the matter decelerated in the stellar wind. The necessary mass-loss rate would need to be unusually low for a Wolf-Rayet star, $\sim 4 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$, but comparable to what has been inferred from the radio.

However, when one combines the fact that a 20 s long GRB was observed, as well as the X-ray afterglow, the situation is more constrained. The shell described in Waxman (2004b) would not, by itself, produce a GRB unless augmented with more relativistic matter. Matzner & McKee (1999) and Tan et al. (2001) have discussed GRB 980425 being produced by a mildly relativistic shell ($\Gamma \sim 2$) impacting the circumstellar wind, but the necessary energy and mass-loss rate are quite high. Although reliable models of the whole explosion are still lacking, it is likely that GRB 980425 resulted from an asymmetric explosion that involved the ejection of material with a Lorentz factor, along our line of sight, of at least $\Gamma \sim 5$ – 10 , depending on the actual mass-loss rate. Otherwise, the burst duration would have been too long. The asymmetric nature of SN 1998bw is also implied by late-time optical spectroscopy (Mazzali et al. 2001).

If so, then the flat X-ray light curve during the first 100 days is unlikely to have resulted from viewing the principal jet, weak or not, along its axis. The X-ray afterglow should then have faded with a power law not too different from other GRBs. In fact, the nearly flat decay is inconsistent with any relativistic blast wave in which the electrons emit a constant fraction of the energy gained in the shock (Cohen et al. 1998), even in a constant-density medium, and argues against an explosion with a single energy and Lorentz factor seen pole-on.

The data may be more consistent with a powerful burst seen off-axis (Granot et al. 2002). Even along its axis, the burst was probably weaker than most, but the energy per solid angle there could still have been orders of magnitude greater than along our line of sight, accounting for most of the $\sim 3 \times 10^{50}$ ergs inferred from the radio. Because of relativistic beaming, initially off-axis observers see only the lower energy material moving in their direction, but as the core of the jet decelerates, its afterglow is beamed to an increasing angle, so that more and more energetic material becomes visible. Depending on the geometry, the afterglow luminosity could even temporarily increase. Granot et al. (2002) considered the appearance of GRB 980425 at various angles and concluded that the viewing angle needs to have been $\gtrsim 3\theta_0$, with θ_0 the half-angle of the

most energetic part of the jet; otherwise, the optical afterglow would have contaminated the supernova light curve unacceptably. One expects that the X-ray light curve would look similar to some of the plots of Granot et al. (2002) with the critical addition of low-energy wings of ejecta as calculated by Zhang et al. (2004). This material would raise the luminosity at early times when almost nothing is seen of the central jet.

As time passes, beaming becomes less important, and the entire decelerating jet becomes visible, followed a little later by the underlying supernova. The light curve should then decline, as it did between days 200 and 1281 in Figure 3. One can estimate the timescale for when beaming becomes unimportant. For a circumstellar density distribution $\rho = Ar^{-2}$, Waxman et al. (1998), assuming typical mass-loss and GRB parameters, estimate a radius

$$r_{\text{NR}} = \frac{E}{4\pi A c^2} = 1.8 \times 10^{18} \frac{E_{52}}{A_*} \text{ cm} \quad (4)$$

and a corresponding time

$$t_{\text{NR}} = \frac{r_{\text{NR}}}{c} = 1.9(1+z) \frac{E_{52}}{A_*} \text{ yr} \quad (5)$$

when the explosion has swept up a rest mass comparable to the initial relativistic ejecta. Here $A_* = A/5 \times 10^{11} \text{ g cm}^{-1}$, corresponding to a fiducial mass-loss rate of $1.0 \times 10^{-5} M_\odot \text{ yr}^{-1}$ for a wind velocity of 1000 km s^{-1} , and E_{52} is the relativistic energy in $10^{52} \text{ ergs s}^{-1}$. In the case of GRB 980425, both A_* and E_{52} may have been less than the fiducial values. One thus expects that for times of the order of several years, the relativistic energy will have been radiated away, and the emission will become isotropic. We can define this as the onset of the supernova stage.

Evidence of a close association of the early X-ray emission to the overall GRB phenomenon is also presented by Berger et al. (2003a). They have studied a sample of 41 GRB X-ray afterglows, and they find a strong correlation between their X-ray isotropic luminosities ($L_{X,\text{iso}}$) (normalized to $t = 10 \text{ hr}$ after trigger) and their beaming fractions. We plot $L_{X,\text{iso}}$ as a function of the GRB isotropic equivalent gamma-ray energy, E_{iso} (Fig. 5). The data are taken from Berger et al. (2003a), and we have added data for GRBs 031203, 030329, and 980425, as indicated on the plot. Several points are striking in this empirical relation: GRBs 031203 and 980425 fall well within the overall correlation and extend the association by roughly 3 orders of magnitude. We have fitted the data with (solid line) and without (dashed line) all the outliers (980425, 031203, 000210, and 990705), with power laws of indices 0.61 and 0.72, respectively; we conclude that the data are consistent with a trend extending roughly 6 orders of magnitude in X-ray luminosity. Parenthetically, the two outliers in the plot correspond to GRB 000210 (a “dark” GRB) and GRB 990705 (a very bright GRB) and indicate that it may be possible to distinguish GRB subclasses simply by using their X-ray and gamma-ray properties, as also pointed out by Berger et al. (2003a).

Note that the convergence to a “supernova” at 3–10 yr here does not require all XRFs and GRBs to have a bright optical supernova following the GRB. Bright optical emission is a statement about the radioactivity of the supernova. X-ray emission at 3 yr is about its kinetic energy. If the variation in the GRB energy and X-ray light curve is simply an effect of viewing angle, then one will expect the empty parameter space

FIG. 5.—Isotropic equivalent luminosity of GRB X-ray afterglows, L_X , scaled to $t = 10 \text{ hr}$ after the burst as a function of their isotropic equivalent gamma-ray energy, E_{iso} . The data are taken from Berger et al. (2003a); here we have added data for GRBs 031203, 030329, and 980425, as indicated on the plot. The solid line shows a fit including all data; the dashed line shows a fit excluding GRBs 980425, 031203, 000210, and 990705.

in Figures 3 and 5 to fill in with future observations. The recent GRB 031203 (Figs. 3 and 5) may well be the first of these “gap” events (Rodríguez-Pascual et al. 2003; Soderberg et al. 2003b) if the reported redshift of $z = 0.105$ (Prochaska et al. 2003) is confirmed.

6. CONCLUSIONS

Our study resulted in the detection, on day 1281, of multiple X-ray point sources in the two *BeppoSAX* error boxes S1 and S2 originally given (Pian et al. 2000) for the variable X-ray counterpart to GRB 980425 (§ 3.1). Based on the accurately known radio location (Kulkarni et al. 1998), the source S1a is definitely the supernova (Fynbo et al. 2000; Sollerman et al. 2002). The sum of all sources in S2 on day 1281 is similar to the maximum observed for this error box by *BeppoSAX* by a factor that is smaller than 1.5. This is consistent with the hypothesis that S2 did not contain the GRB but instead some variable X-ray sources that have not disappeared. S1, however, has been consistently observed to decline for ~ 1300 days, thus leading us to believe that source S1 contained the GRB and that SN 1998bw and GRB 980425 were the same explosion.

Additional insight comes when we compare the X-ray light curve of GRB 980425 with the broader family of high-energy transients (§ 4). Comparison of published X-ray light curves for GRBs, XRFs, and supernovae supports a “unification hypothesis,” similar to that proposed for active galactic nuclei. Under this hypothesis all of these sources are associated with supernova explosions of massive stars (although the supernova may not be a typical one). We can also distinguish a “strong unification hypothesis,” in which the properties of the external medium are also standardized. There is considerable, although still inconclusive, evidence that the strong unification hypothesis is false, although it is still worth testing. These

explosions are conjectured to produce an anisotropic, beamed component associated with a decelerating, ultrarelativistic outflow and an unbeamed, isotropic component associated with the slowly expanding stellar debris. The flux associated with the beamed component depends on the observer direction and declines rapidly with observer time; the closer to the axis, the larger the flux and the more rapid the onset of the typical afterglow decline. As the beamed component decelerates to become entirely nonrelativistic, the observed flux will become independent of orientation. Under the strong unification hypothesis, a one-parameter (inclination) family of X-ray light curves will be produced, converging asymptotically to a single variation when the beamed component becomes nonrelativistic. If only the unification hypothesis is true, we should still be able to observe these trends and estimate the inclination. Indeed, this is roughly what we observe when we plot the isotropic luminosities of GRBs, XRFs, and supernovae on a common scale (Fig. 3). It appears that after 3 yr all explosions are subrelativistic, with X-ray luminosity dominated by the stellar debris, $\sim 10^{39}$ ergs s $^{-1}$. We therefore tentatively identify GRBs, XRFs, and supernovae as similar objects observed with small, medium, and large inclination, respectively. More specific to this paper, the observation that SN 1998bw and GRB 980425 follow a smooth light curve that fits this pattern supports the claim that they are the same source.

In § 5 we discussed two possible interpretations of these light curves based on being either a standard phenomenon viewed at different angles or explosions that eject variable amounts of relativistic ejecta. We conclude that the observations, especially the slow initial decline rate, are more consistent with the off-axis model in which GRB 980425 was a much more powerful GRB seen at an angle greater than about 3 times the opening angle of the central jet. In this model, emission at early times does not come from this central jet but from wings of less energetic material. After about 3 yr the emission of all these high-energy transients becomes isotropic, and we see the subrelativistic ejecta of the supernova interacting with the circumstellar wind. Thus, all high-energy transients have a common luminosity at 3 yr because of their nonrelativistic ejecta, but they follow different decay rates, depending on the viewing angle, to get there.

Furthermore, we discussed the stellar environment in that region of galaxy ESO 184-G82 where the supernova occurred. The supernova is one member of an X-ray doublet, both of

which seem to be in the galaxy and to have spent part of their life cycles as ULXs. The projected distance between the two X-ray sources is ~ 300 pc, which is suggestive of some sort of a very active star-forming region.

Finally, we would like to stress that the existence of a relation between the decline rate of the X-ray light curve during the first few weeks and its brightness implies that such measurements might be useful for diagnosing the character and subsequent evolution of a given high-energy transient, as well as for constraining its distance. However, the sparse coverage of the current X-ray afterglow data does not allow us to address fundamental questions such as: Did the rapid decline of GRB 980425 continue? Did it/will it level out above or in the vicinity of other Type Ib/c supernovae? At what point does SN 1998bw become like ordinary supernovae? The current data enable us to make a *prediction* on the unification of the GRB and supernova phenomena, which can only be vindicated with further observations, obviously of SN 1998bw, but also of the nearest XRFs and GRBs to fill in the missing parameter space. We strongly encourage, therefore, follow-up observations of nearby GRBs and XRFs for as long as the available instrumentation allows; we also encourage the calculation of off-axis models of the X-ray light curves, especially for a variable distribution of Lorentz factors and energies.

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REFERENCES

- Berger, E., Kulkarni, S. R., & Frail, D. A. 2003a, *ApJ*, 590, 379
 Berger, E., et al. 2003b, *Nature*, 426, 154
 Björnsson, G., Hjorth, J., Pedersen, K., & Fynbo, J. U. 2002, *ApJ*, 579, L59
 Bloom, J. S., Frail, D. A., & Kulkarni, S. R. 2003, *ApJ*, 594, 674
 Bregman, J. N., Houck, J. C., Chevalier, R. A., & Roberts, M. S. 2003, *ApJ*, 596, 323
 Butler, N., et al. 2003, *GCN Circ.* 2347 (<http://gcn.gsfc.nasa.gov/gcn/gcn3/2347.gcn3>)
 Cash, W. 1979, *ApJ*, 228, 939
 Chevalier, R. A., & Li, Z. 2000, *ApJ*, 536, 195
 Cohen, E., Piran, T., & Sari, R. 1998, *ApJ*, 509, 717
 Costa, E., et al. 1997, *Nature*, 387, 783
 Fabbiano, G. 1989, *ARA&A*, 27, 87
 Fabbiano, G., et al. 2003, *ApJ*, 584, L5
 Fox, D. B., Soderberg, A. M., Kulkarni, S. R., & Frail, D. 2004, *GCN Circ.* 2522 (<http://gcn.gsfc.nasa.gov/gcn/gcn3/2522.gcn3>)
 Frail, D. A., et al. 2001, *ApJ*, 562, L55
 Freedman, W. L., Kennicutt, R. C., Jr., Mould, J. R., & Madore, B. F. 2003, in *A Decade of Hubble Space Telescope Science*, ed. M. Livio, K. Noll, & M. Stiavelli (Cambridge: Cambridge Univ. Press), 214
 Fynbo, J. U., et al. 2000, *ApJ*, 542, L89
 Galama, T., et al. 1998, *Nature*, 395, 670
 Giacconi, R., et al. 2001, *ApJ*, 551, 624
 Granot, J., Panaitescu, A., Kumar, P., & Woosley, S. E. 2002, *ApJ*, 570, L61
 Greiner, J., Cuby, J. G., & McCaughrean, M. J. 2001, *Nature*, 414, 522
 Greiner, J., Morgan, E. H., & Remillard, R. A. 1996, *ApJ*, 473, L107
 Harrison, F. A., et al. 2001, *ApJ*, 559, 123
 Heise, J. 2003, in *AIP Conf. Ser.* 662, *Gamma-Ray Burst and Afterglow Astronomy 2001: A Workshop Celebrating the First Year of the HETE Mission*, ed. G. R. Ricker & R. K. Vanderspek (Melville: AIP), 229
 Hjorth, J., et al. 2003, *Nature*, 423, 847
 Humphrey, P. J., Fabbiano, G., Elvis, M., Church, M. J., & Bałucińska-Church, M. 2003, *MNRAS*, 344, 134
 Immler, S., Wilson, A. S., & Terashima, Y. 2002, *ApJ*, 573, L27
 Iwamoto, K., et al. 1998, *Nature*, 395, 672
 Kaaret, P., Corbel, S., Prestwitt, A. H., & Zezas, A. 2003, *Science*, 299, 365
 Kouveliotou, C., et al. 1993, *ApJ*, 413, L101
 Kulkarni, S., et al. 1998, *Nature*, 395, 663
 Li, Z., & Chevalier, R. A. 1999, *ApJ*, 526, 716
 MacFadyen, A., & Woosley, S. 1999, *ApJ*, 524, 262
 Matzner, C. D., & McKee, C. F. 1999, *ApJ*, 510, 379
 Mazzali, P. A., Nomoto, K., Patat, F., & Maeda, K. 2001, *ApJ*, 559, 1047

- Mészáros, P., Rees, M. J., & Wijers, R. A. M. J. 1998, *ApJ*, 499, 301
- Mirabel, I. F., & Rodríguez, L. F. 1994, *Nature*, 371, 46
- Mori, K., Tsunemi, H., Miyata, E., Baluta, C. J., Burrows, D. N., Garmire, G. P., & Chartas, G. 2001, in *ASP Conf. Ser. 251, New Century of X-Ray Astronomy*, ed. H. Inoue & H. Kunieda (San Francisco: ASP), 576
- Nakamura, T. 1999, *ApJ*, 522, L101
- Paczynski, B. 1998, *ApJ*, 494, L45
- Pian, E., et al. 2000, *ApJ*, 536, 778
- . 2001, *A&A*, 372, 456
- . 2004, *Adv. Space Res.*, in press (astro-ph/0304521)
- Piro, L., et al. 2001, *ApJ*, 558, 442
- Pooley, D., et al. 2002, *ApJ*, 572, 932
- Prochaska, J., et al. 2003, *GCN Circ.* 2482 (<http://gcn.gsfc.nasa.gov/gcn/gcn3/2482.gcn3>)
- Ramirez-Ruiz, E., Celotti, A., & Rees, M. J. 2002, *MNRAS*, 337, 1349
- Rhoads, J. E. 1997, *ApJ*, 487, L1
- Roberts, T. P., & Warwick, R. S. 2000, *MNRAS*, 315, 98
- Rodríguez-Pascual, P., Santos-Lleo, M., Gonzalez-Riestra, R., Schartel, N., & Altieri, B. 2003, *GCN Circ.* 2474 (<http://gcn.gsfc.nasa.gov/gcn/gcn3/2474.gcn3>)
- Rossi, E., Lazzati, D., & Rees, M. J. 2002, *MNRAS*, 332, 945
- Sako, M., & Harrison, F. A. 2002a, *GCN Circ.* 1624 (<http://gcn.gsfc.nasa.gov/gcn/gcn3/1624.gcn3>)
- . 2002b, *GCN Circ.* 1716 (<http://gcn.gsfc.nasa.gov/gcn/gcn3/1716.gcn3>)
- Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, 500, 525
- Soderberg, A. M., Frail, D. A., & Wieringa, M. H. 2004, *ApJL*, submitted (astro-ph/0402163)
- Soderberg, A. M., et al. 2003a, *ApJ*, in press (astro-ph/0311050)
- . 2003b, *GCN Circ.* 2483 (<http://gcn.gsfc.nasa.gov/gcn/gcn3/2483.gcn3>)
- Sollerman, J., et al. 2002, *A&A*, 386, 944
- Soria, R., Pian, E., & Mazzali, P. A. 2004, *A&A*, 413, 107
- Stanek, K. Z., et al. 2003, *ApJ*, 591, L17
- Sutaria, F. K., Chandra, P., Bhatnagar, S., & Ray, A. 2003, *A&A*, 397, 1011
- Swartz, D. A., Ghosh, K. K., Suleimanov, V., Tennant, A. F., & Wu, K. 2002, *ApJ*, 574, 382
- Tan, J. C., Matzner, C. D., & McKee, C. F. 2001, *ApJ*, 551, 946
- Tiengo, A., Mereghetti, S., Ghisellini, G., Rossi, E., Ghirlanda, G., & Schartel, N. 2003, *A&A*, 409, 983
- Tiengo, A., Mereghetti, S., Ghisellini, G., Tavecchio, F., & Ghirlanda, G. 2004, *A&A*, in press (astro-ph/0402644)
- Tsunemi, H., Mori, K., Miyata, E., Baluta, C. J., Burrows, D. N., Garmire, G. P., & Chartas, G. 2001, *ApJ*, 554, 496
- Uno, S., et al. 2002, *ApJ*, 565, 419
- van Paradijs, J., Kouveliotou, C., & Wijers, R. A. M. J. 2000, *ARA&A*, 38, 379
- Watson, D., et al. 2004, *ApJ*, 605, L101
- Waxman, E. 2004a, *ApJ*, 602, 886
- . 2004b, *ApJ*, 605, L97
- Waxman, E., Kulkarni, S. R., & Frail, D. A. 1998, *ApJ*, 497, 288
- Woosley, S. E. 1993, *ApJ*, 405, 273
- Woosley, S. E., Eastman, R. G., & Schmidt, B. P. 1999, *ApJ*, 516, 788
- Yamazaki, R., Yonetoku, D., & Nakamura, T. 2003, *ApJ*, 594, L79
- Zezas, A., Fabbiano, G., Rots, A. H., & Murray, S. 2002, *ApJ*, 577, 710
- Zhang, W., Woosley, S. E., & Heger, A. 2004, *ApJ*, 608, 365