THE ASTROPHYSICAL JOURNAL, 536:778–787, 2000 June 20


# *BeppoSAX* OBSERVATIONS OF GRB 980425: DETECTION OF THE PROMPT EVENT AND MONITORING OF THE ERROR BOX

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*Received 1999 October 12; accepted 2000 January 31*

## ABSTRACT

We present *BeppoSAX* follow-up observations of GRB 980425 obtained with the Narrow Field Instruments (NFI) in 1998 April, May, and November. The first NFI observation has detected within the 8′ radius error box of the gamma-ray burst (GRB) an X-ray source positionally consistent with the supernova 1998bw, which exploded within a day of GRB 980425, and a fainter X-ray source, not consistent with the position of the supernova. The former source is detected in the following NFI pointings and exhibits a decline of a factor of 2 in six months. If it is associated with SN 1998bw, this is the first detection of X-ray emission from a Type I supernova above 2 keV. The latter source exhibits only marginally significant variability. The X-ray spectra and variability of the supernova are compared with thermal and nonthermal models of supernova high-energy emission. Based on the *BeppoSAX* data, it is not possible to establish firmly which of the two detected sources is the GRB X-ray counterpart, although probability considerations favor the supernova.

*Subject headings:* gamma rays: bursts — supernovae: individual (SN 1998bw)

## 1. INTRODUCTION

The gamma-ray burst (GRB) of 1998 April 25, detected both by the *BeppoSAX* Gamma-Ray Burst Monitor (GRBM) and by BATSE (Kippen 1998) and localized with arcminute accuracy by the *BeppoSAX* Wide-Field Cameras (WFCs) (Soffitta et al. 1998), has received particular attention from astronomers because of its spatial (within a few arcminutes) and temporal (within one day) consistency with the optically and exceedingly radio bright Type Ic supernova 1998bw (Galama et al. 1998; Kulkarni et al. 1998a; Iwamoto et al. 1998) in the nearby galaxy ESO 184-G82 ($z = 0.0085$; Tinney et al. 1998). The low probability of a chance coincidence between the two events ($\sim 10^{-4}$; Galama et al. 1998) has strengthened the hypothesis of a physical association between GRB 980425 and the supernova.

However, since the other GRBs for which a redshift measurement is available are located at larger distances ($z \sim 0.7$ or higher) and are characterized by power-law decaying optical afterglows (Fruchter et al. 1999a; Djorgovski et al. 1997; Fruchter et al. 2000; Halpern et al. 1998; Kulkarni et al. 1998b; Bloom et al. 1998a; Vreeswijk et al. 1999; Castro-Tirado et al. 1999; Galama et al. 1999a; Kulkarni et al. 1999; Fruchter et al. 1999b; Harrison et al. 1999; Stanek et al. 1999; Sahu et al. 2000), in agreement with the "classical" fireball model (e.g., Rees & Mészáros 1992; Piran 1999), GRB 980425 has been regarded as a possible representative of a separate GRB class, with apparently indistinguishable high-energy characteristics, but with different progenitors.

The existence of a particular class of GRBs and its possible association with supernovae have been systematically searched for by several authors using BATSE catalogs and supernovae compilations (Wang & Wheeler 1998; Norris, Bonnell, & Watanabe 1999; Bloom et al. 1998b; Kippen et al. 1998) or based on individual cases of supernovae with outstanding optical properties (Germany et al. 2000; Turatto et al. 1999; Terlevich, Fabian, & Turatto 1999).

Following the detection of GRB 980425, observations of its WFC error box with the *BeppoSAX* Narrow Field Instruments (NFI) were immediately activated, starting 10 hours and one week after the event. The detection of two previously unknown X-ray sources—one of which being consistent with the position of the supernova and the other possibly, but not clearly, fading—was regarded as quite anomalous, because previous *BeppoSAX* NFI follow-up observations of well-localized GRBs had generally detected X-ray transients characterized by power-law decay. This fact prompted further observations six months after the event, aimed at clarifying the uncertainty about the GRB X-ray counterpart and, as a secondary though not less important scope, at monitoring the X-ray emission of SN 1998bw, considering the peculiarity of this object and the poor knowledge of the X-ray behavior in supernovae in

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general (see review by Schlegel 1995) and particularly of Type I supernovae.

In this paper we present the high-energy characteristics of the prompt event as measured by the *BeppoSAX* GRBM and WFC and the results of the follow-up NFI observations (§ 2) and discuss their implications in view of the detection of SN 1998bw in the GRB field (§ 3). A preliminary report on these data has been given in Pian et al. (1999).

## 2. DATA ANALYSIS AND RESULTS

### 2.1. *Prompt Event*

GRB 980425 triggered the *BeppoSAX* GRBM at 21:49:11 UT and was simultaneously detected by the *BeppoSAX* WFC unit 2 (Soffitta et al. 1998). The event had a duration of 31 s in the range 40–700 keV and 40 s in the range 2–26 keV. It exhibited a single, nonstructured peak profile in both bands (Fig. 1). Some flux brightening and successive decrease, lasting altogether ∼10 s, are seen in the WFC light curve after the first 40 s but not in the $\gamma$-rays.

The GRBM and WFC light curves appear well correlated, with the indication of a ∼5 s lag of the lower energies with respect to the higher energies. Figure 2 shows the discrete correlation function (DCF) between the two light curves. This correlation method is suited to searching for correlations and temporal lags between two discrete and possibly unevenly sampled data trains (Edelson & Krolik 1988). A maximum of the DCF amplitude at a positive temporal lag corresponds to positive correlation, with the higher energies leading the lower ones. A maximum at a positive temporal lag of ∼5 s is evident. The asymmetric shape of the DCF function amplitude around its peak reflects the fact that the flux decay after maximum is slower at X-rays than at $\gamma$-rays (see Fig. 1).

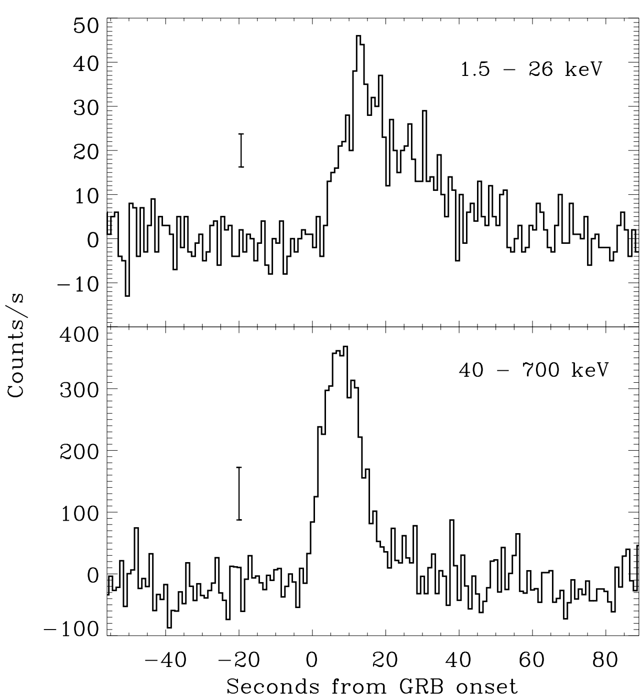


FIG. 1.—*BeppoSAX* WFC (*top*) and GRBM (*bottom*) light curves of GRB 980425. The onset of the GRB, indicated by the zero abscissa, corresponds to 1998 April 25.909097 (i.e., 5 s earlier than the GRBM trigger time). The vertical bars represent the typical 1 $\sigma$ uncertainty associated with the individual flux points.

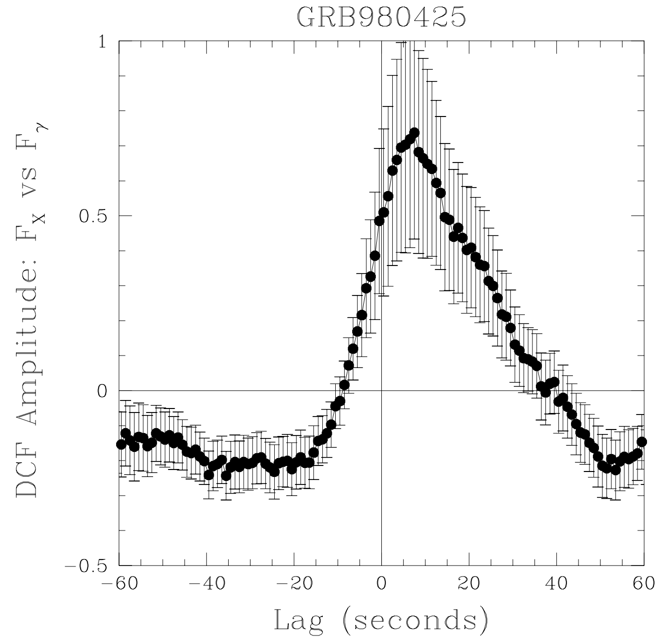


FIG. 2.—Discrete correlation function between WFC and GRBM light curves. The maximum at ∼5 s indicates positive correlation between the two curves with the WFC light curve lagging the GRBM light curve by that temporal lag.

The fluences are $(2.8 \pm 0.5) \times 10^{-6}$ and $(1.8 \pm 0.3) \times 10^{-6}$ ergs cm$^{-2}$ in the 40–700 and 2–26 keV energy range, respectively. (The Galactic absorption in the direction of GRB 980425, $N_{\rm H_I} = 4 \times 10^{20}$ cm$^{-2}$, from Schlegel, Finkbeiner, & Davis 1998, is negligible at energies higher than 2 keV.) The spectral index of the $\gamma$-ray spectrum, averaged over the burst duration, is $\alpha = 1.2 \pm 0.2$ ($f_\nu \propto \nu^{-\alpha}$), and that of the X-ray spectrum is $\alpha = 0.41 \pm 0.25$. Strong spectral softening is evident during the event (Frontera et al. 2000). No peculiar temporal or spectral characteristics are noted in this GRB.

The spacecraft aspect reconstruction conditions allowed us to only poorly constrain the WFC error box of the GRB, which has a radius of 8′. This made the search of an X-ray transient more difficult. The Interplanetary Network (IPN) allowed a substantial reduction of the GRB error box (see Galama et al. 1999b).

### 2.2. *NFI Target of Opportunity Observations*

The *BeppoSAX* NFI were pointed at the 8′ radius error box determined by the WFC at three epochs, the first starting 10 hr after the GRB: April 26–28, May 2–3, and November 10–12 (see Journal of Observations in Table 1; note that the April pointing was uninterrupted but has been split in two parts only for the purpose of data analysis). The strategy of performing NFI pointings at such large time intervals after the GRB (one week and six months), in addition to promptly thereafter, is not usually adopted for GRBs and was dictated by the ambiguity of the results obtained with the April observation, which suggested quite a different case than previously observed X-ray afterglows.

Event files for the Low Energy Concentrator Spectrometer (LECS) and Medium Energy Concentrator Spectrometer (MECS) experiments were linearized and cleaned with SAX Data Analysis System (SAXDAS) at the *BeppoSAX* Science Data Center (SDC; Giommi & Fiore

TABLE 1
JOURNAL OF *BeppoSAX* LECS AND MECS OBSERVATIONS

| DATE (UT) | LECS $t^a$ (s) | LECS Flux[b] ($\times 10^{-3}$ counts $s^{-1}$) S1 | LECS Flux[b] S2 | MECS $t^a$ (s) | MECS Flux[c] ($\times 10^{-3}$ counts $s^{-1}$) S1 | MECS Flux[c] S2 |
|---|---|---|---|---|---|---|
| 1998 Apr 26.334–27.458 ....... | 24,483 | $4.0 \pm 1.3^d$ | <4.0 | 37,220 | $4.6 \pm 0.6$ | $2.4 \pm 0.5$ |
| 1998 Apr 27.469–28.160 ....... | 13,566 | <7.0 | <7.0 | 21,805 | $4.5 \pm 0.7$ | <2.5 |
| 1998 May 02.605–03.621 ...... | 1016.5 | ... | ... | 31,975 | $3.0 \pm 0.5$ | $1.4^e \pm 0.5$ |
| 1998 Nov 10.754–12.004 ...... | 16,961 | <6.0 | <6.0 | 53,122 | $1.8 \pm 0.4$ | <2.0 |

[a] On-source exposure time.
[b] In the energy range 0.1–4 keV.
[c] In the energy range 1.6–10 keV.
[d] All uncertainties are at 1 $\sigma$; upper limits are at 3 $\sigma$.
[e] The 3 $\sigma$ upper limit is $1.9 \times 10^{-3}$ counts $s^{-1}$.

1998). LECS (0.1–4 keV) and MECS (units 2 and 3, 1.6–10 keV) images for each pointing were extracted using the XIMAGE software package. The MECS images, better exposed and of higher signal-to-noise ratio than the LECS images, are reported in Figure 3.

The analysis of the MECS imaging data of the first portion of the first pointing (Fig. 3*a*) shows that inside the intersection of the WFC error circle and IPN annulus, two pointlike, previously unknown X-ray sources are detected with a positional uncertainty of 1'.5: 1SAX J1935.0−5248 (hereafter S1), at R.A. = $19^h35^m05^s.9$ and decl. = −52°50′03″, and 1SAX J1935.3−5252 (hereafter S2), at R.A = $19^h35^m22^s.9$ and decl. = −52°53′49″. Note that the coordinates distributed by Pian et al. (1998) were revised in 1998 November to take into account a systematic error due to the nonoptimal spacecraft attitude during the 1998 April and May observations (see Piro et al. 1998a). The revised position of S1 is consistent within the uncertainty with the position of SN 1998bw detected in the WFC error box (Galama et al. 1998; Kulkarni et al. 1998a) and exploded simultaneously with the GRB with an uncertainty of ∼1 day (Iwamoto et al. 1998), while the revised position of S2 is ∼4'.5 away from SN 1998bw and therefore inconsistent with it (see Fig. 1 in Galama et al. 1999b).

The LECS and MECS count rates and upper limits for both sources during the three pointings have been computed within circles of 3′ radius and corrected for the local background estimated within circles of similar size (Table 1). The upper limits have been estimated as explained in the Appendix. This method takes into account, in addition to the normal photon statistics, the fact that at these flux levels the LECS and MECS background may be dominated by the fluctuations of the cosmic X-ray background.

Source S1 is detected by the MECS also in the following pointings at a position consistent with that of the first observation. The observation of 1998 November shows a decrease in the X-ray flux of approximately a factor of 2 with respect to the level measured in 1998 April–May. The source is also detected by the LECS in the April pointing and not in the November pointing (LECS data of the 1998 May pointing are excluded from the analysis because of the extremely short exposure time).

Because of the limited spatial resolution of the LECS and MECS detectors and the faint emission level of source S2, estimating its flux is made difficult by the background contamination and by the proximity of the brighter source S1. During the second portion of the April pointing, as well as in the 1998 November pointing, S2 is not detected by the MECS, while signal from a position consistent with that of S2 in April is marginally detected in the 1998 May pointing (Fig. 3*c*), with lower flux than in the first observation (see Table 1) but consistent with it within ∼2 $\sigma$. We note that the May detection, albeit of a signal-to-noise ratio formally lower than 3, has a very low probability of being a background fluctuation (∼$10^{-6}$) when considered together with the April detection. However, we conservatively report in Table 1 also the 3 $\sigma$ upper limit for the May measurement. All upper limits to the flux of S2 are consistent with the level of the detection. There is no significant detection of S2 in the individual LECS images.

No significant signal above background is detected by the *BeppoSAX* high-energy instruments Phoswich Detection System (PDS) and High Pressure Gas Scintillation Proportional Counter (HPGSPC) in any of the three pointings.

Light curves and spectra for each pointing were accumulated with the XSELECT tool, using a 3′ extraction radius both for the LECS and for the MECS, which provides only 80% of flux but allows partial avoidance of the mutual contamination of S1 and S2. Since the local background intensity is similar to that measured from files accumulated from blank fields available at the SDC, we used the latter, which are affected by a smaller uncertainty. No significant variability within each pointing is exhibited by either source.

Spectral analysis of the LECS and MECS data has been done with the XSPEC 10.0 package using the response matrices and auxiliary files available at the SDC. LECS and MECS spectra flux distributions of both sources have been grouped in order to achieve a signal-to-noise ratio of at least ∼3 in each bin.

For S1, a fit with a single power law ($F_\nu \propto \nu^{-\alpha}$) absorbed by Galactic extinction of the individual MECS spectra is satisfactory, with reduced $\chi^2$ values well below 1 due to the large errors. For these fits at individual epochs, the LECS spectra have not been used because they have too low signal-to-noise ratios.

Since no significant spectral variability is seen from epoch to epoch, we averaged the LECS and MECS spectra of April and May to increase the signal-to-noise ratio and

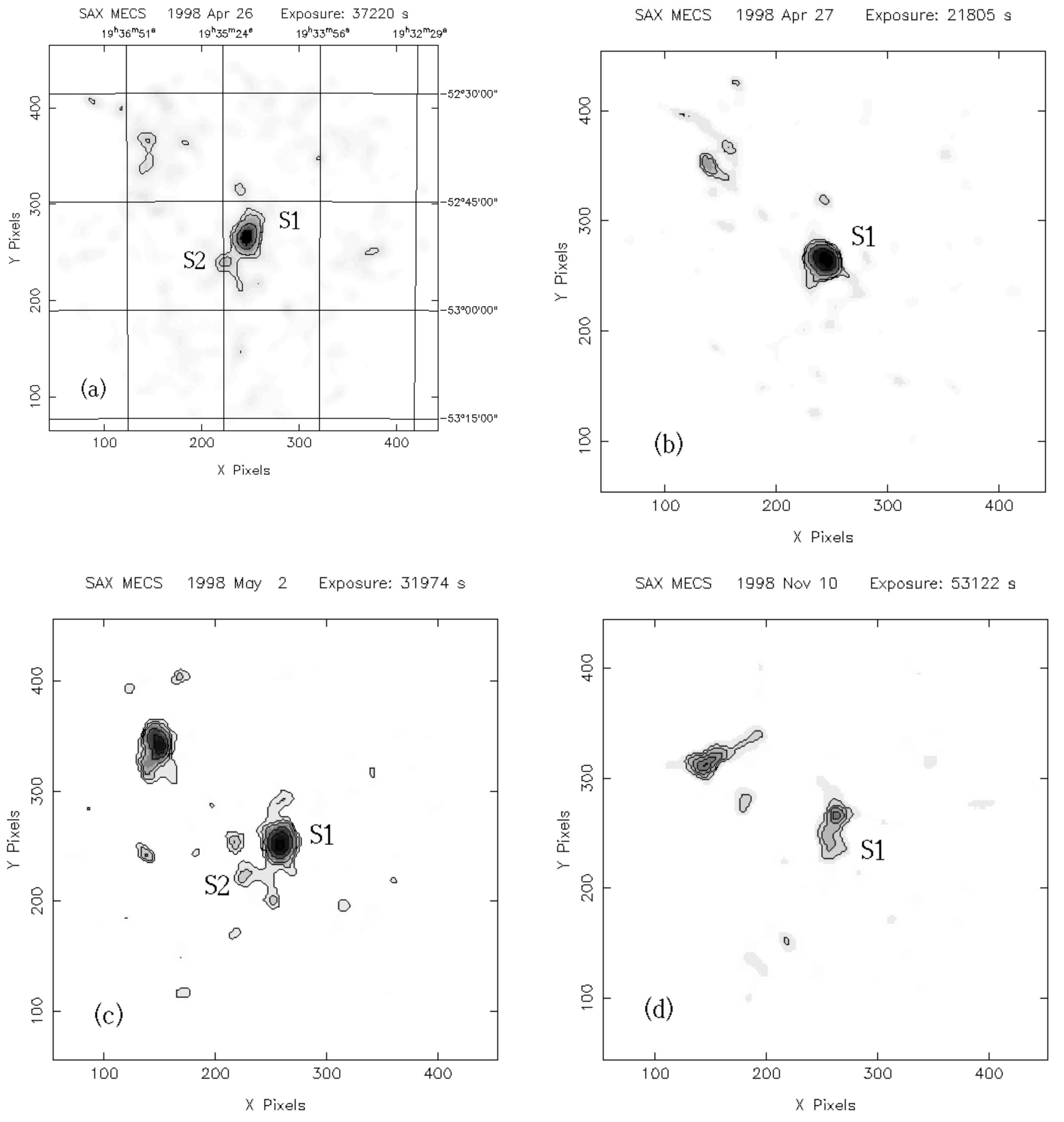


FIG. 3.—*BeppoSAX* MECS images of the field of GRB 980425 in the energy band 1.6–10 keV referring to the epochs (*a*) 1998 April 26.334–27.458, (*b*) April 27.469–28.160, (*c*) May 2.605–3.621, (*d*) November 10.754–12.004. The local background has been subtracted, and a smoothing has been applied with a window function of width comparable to the MECS detector point-spread function (3′ at half-power diameter). The source S1 is clearly seen in all images. The fainter source S2 is detected (*a*) in the first part of the first pointing and (*c*) in the 1998 May pointing. Note that in (*c*) 1998 May the pointing center was significantly displaced with respect to the April pointing, which accounts for the presence of the bright source toward the northeast, about 9′ from the image center, not visible in (*a*) and (*b*). In each image, the most external contours represent 2 $\sigma$ flux levels.

fitted a single power law to the average rebinned spectrum. We excluded the November spectrum from this average because the count rates indicate that the flux varied at that epoch with respect to April–May (Table 1).

We obtain a spectral index of $\alpha = 1.0 \pm 0.3$ (all fit parameters for the average spectrum are reported in Table 2). The fitted $N_{\rm H\,I}$ is found to be consistent with the Galactic value, and therefore we have fixed it to that value. The intercalibration constant between the LECS and MECS data is within the expected range. However, the fit is formally not completely satisfactory (reduced $\chi^2 = 1.2$, see Table 2), because of a flux excess at energies below $\sim 1$ keV (Fig. 4*a*). We also tried a fit with a thermal bremsstrahlung with Galactic absorption, obtaining a temperature $kT \simeq 8$ keV

TABLE 2

FITS TO THE *BeppoSAX* LECS + MECS AVERAGE SPECTRUM OF S1 IN 1998 APRIL–MAY

| Model | $\alpha_1$ | $\alpha_2$ | $E_{\rm break}$ (keV) | $kT_{\rm THB}$ (keV) | $kT_{\rm BB}$ (keV) | Reduced $\chi^2$ | dof |
|---|---|---|---|---|---|---|---|
| Single Power-Law | $1.0 \pm 0.3$ | ... | ... | ... | ... | 1.18 | 12 |
| Thermal Bremsstrahlung | ... | ... | ... | $7.5^{+13.5}_{-3.5}$ | ... | 1.66 | 12 |
| Broken Power-Law | $2.0 \pm 0.5$ | $0.7 \pm 0.4$ | $1.4 \pm 0.6$ | ... | ... | 0.49 | 9 |
| Power-Law + Blackbody | $0.5 \pm 0.3$ | ... | ... | ... | $90^{+30}_{-20}$ | 0.49 | 10 |
| Thermal Bremsstrahlung + Blackbody | ... | ... | ... | $16^{+130}_{-10}$ | $90^{+30}_{-20}$ | 0.46 | 10 |

NOTE.—Uncertainties are at 90% (1.6 $\sigma$) confidence level.

and an unsatisfactory reduced $\chi^2$ of 1.7, still due to the presence of a soft excess (Fig. 5*a*).

Fitting the data assuming no Galactic absorption still yields some soft excess with respect to both a power-law and a bremsstrahlung model; therefore, we tend to exclude that the effect is due to an overestimate of the Galactic extinction in the direction of SN 1998bw (as suggested by Patat et al. 2000).

A fit of the data with a broken power law and Galactic absorption yields an index $\alpha_1 = 2.0 \pm 0.5$ below 1.4 keV and $\alpha_2 = 0.7 \pm 0.4$ at the higher energies. The reduced $\chi^2$ is 0.5, considerably lower than for the single power law and for the bremsstrahlung models (see Fig. 6).

To account for the soft excess, we also tried composite fits of a power law or a thermal bremsstrahlung with a blackbody model plus Galactic absorption. The former fit yields a spectral index $\alpha = 0.5 \pm 0.3$ and a blackbody temperature $kT = 90 \pm 20$ eV, with a reduced $\chi^2 = 0.5$ (Fig. 4*b*). The latter yields a bremsstrahlung temperature of $kT \sim 16$ keV (see Table 2) and blackbody temperature and normalization consistent with those found in the former case (reduced $\chi^2 = 0.5$; Fig. 5*b*).

We found no obvious reason for the excess to be spurious, such as instrumental effect or nonoptimal background subtraction. Therefore, we considered it real, although not highly significant (see Figs. 4*a* and 5*a*). The

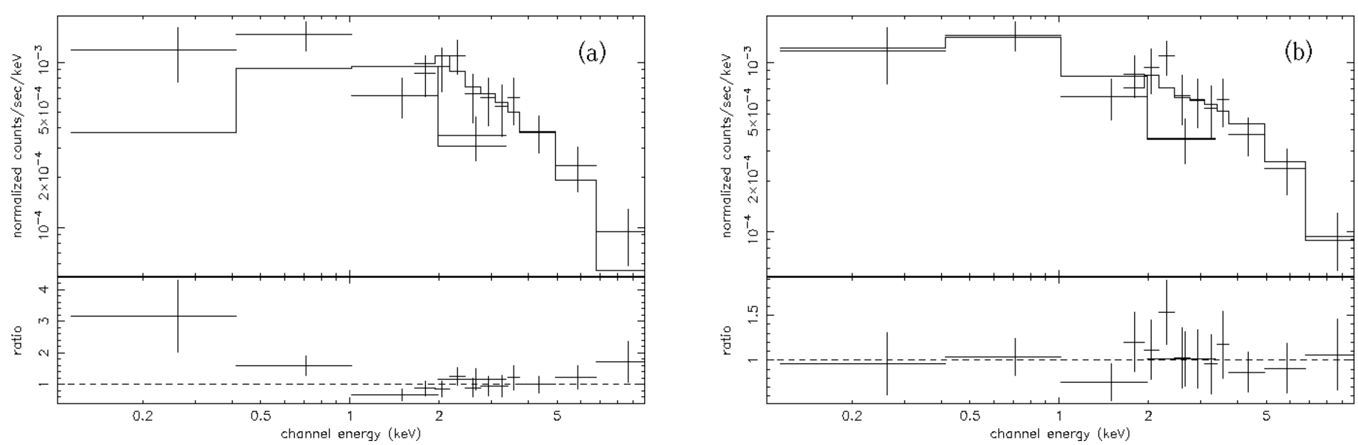


FIG. 4.—*BeppoSAX* LECS and MECS average spectrum of S1 in 1998 April–May fitted with (*a*) a single power law and (*b*) a power law plus blackbody. The lower panels show the ratios between the data and the model. See Table 2 for the fit parameters.

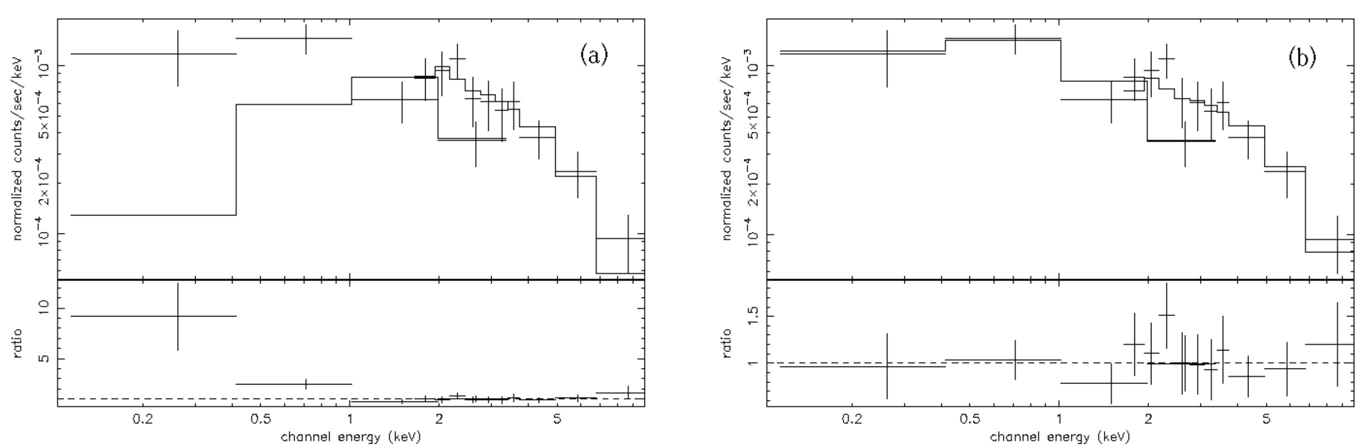


FIG. 5.—*BeppoSAX* LECS and MECS average spectrum of S1 in 1998 April–May fitted with (*a*) a thermal bremsstrahlung and (*b*) a thermal bremsstrahlung plus blackbody. The lower panels show the ratios between the data and the model. See Table 2 for the fit parameters.

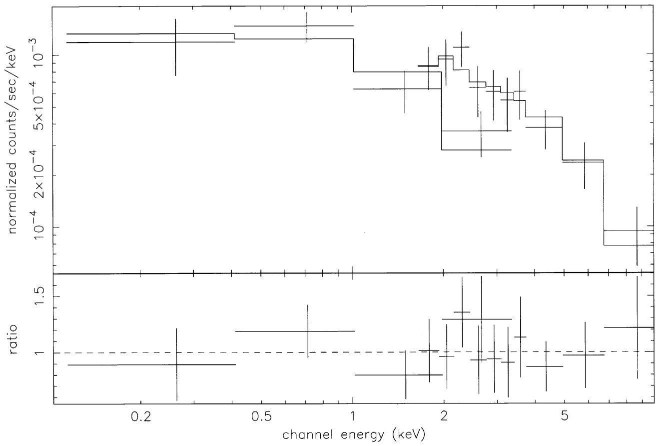


FIG. 6.—*BeppoSAX* LECS and MECS average spectrum of S1 in 1998 April–May fitted with a broken power law. The lower panel shows the ratios between the data and the model. See Table 2 for the fit parameters.

chance probabilities that adding a blackbody component either to a power-law or to a thermal bremsstrahlung model improves the fit are 1.3% and 0.17%, respectively. Fitting the data with a broken instead of a single power law has a chance probability of improvement of 4%.

The low signal-to-noise ratio of the LECS data in 1998 November does not allow us to test the goodness of the fit of those data with a blackbody model. By fixing the blackbody temperature to the best-fit value of the April–May spectrum, 90 eV, and fitting a power law–plus–blackbody model to the November MECS spectrum and LECS upper limit, we get a blackbody normalization upper limit consistent with the value obtained for April–May, indicating that this component has not varied significantly. The power-law normalization has instead varied by a factor of $\sim 2$.

Although there is no detection of S2 in the individual LECS images, signal is present in the April–May co-added image. Therefore, since the MECS spectra of the individual observations have a very low signal-to-noise ratio, we used only the rebinned LECS + MECS spectrum obtained from the average April–May image and fitted it with a power law of index $\alpha = 1.5 \pm 0.4$ plus Galactic absorption ($\chi^2 = 0.5$).

Because of the high uncertainty in the power-law spectral index and to the low level of both S1 and S2, we estimated their intensities in the 2–10 keV band by assuming a standard factor of conversion from count rates of $9.3 \times 10^{-11}$, corresponding to an adopted power-law spectral shape of index 0.5. The 1 $\sigma$ uncertainties on the intensities have been obtained by similarly scaling the errors on the count rates (Table 1). These intensities are reported in Figure 7, along with the WFC light curve in the 2–10 keV band, obtained by binning in intervals of 5–20 s the temporal profile reported in Figure 1. Differences between these intensities and those obtained by adopting a bremsstrahlung model do not exceed 10%. Note that the contribution of the blackbody component to the intensity of S1 in the 2–10 keV range is negligible. The 3 $\sigma$ upper limits computed from the PDS average spectrum of the three pointings in the bands 13–30 keV, 13–60 keV, and 13–100 keV, assuming a photon index $\Gamma = 1.5$, are $2.1 \times 10^{-12}$, $4.6 \times 10^{-12}$, and $7.2 \times 10^{-12}$ ergs $s^{-1}$ $cm^{-2}$, respectively, and are at least a factor of 10 larger than the extrapolations at those energies of the LECS + MECS spectra of both S1 and S2. (Assuming $\Gamma = 2$ or $\Gamma = 2.5$ leads to similar upper limits, within $\sim$20%–30%.)

## 3. DISCUSSION

### 3.1. *Light Curve and Spectral Shape of Source S1*

The X-ray light curve of source S1 measured by the NFIs shows a decay of a factor of 2 in $\sim$6 months (Fig. 7*b*), much slower than X-ray GRB afterglows so far observed. Assuming, as suggested by the positional coincidence and by variability, that S1 is associated with SN 1998bw, this is the first detection of medium-energy X-ray emission from a Type I supernova (there is a unique case of a Type I supernova detected in soft X-rays, the Type Ic SN 1994I; Immler, Pietsch, & Aschenbach 1998a) and the earliest detection of X-rays after a supernova explosion.

At the distance of SN 1998bw, 38 Mpc, the luminosity observed in the range 2–10 keV, $\sim 4\text{–}7 \times 10^{40}$ ergs $s^{-1}$, would be compatible with that of other supernovae detected in the same energy band (Kohmura et al. 1994; Houck et al. 1998; Schlegel 1995 and references therein).

However, the observed luminosity and variation thereof represent only an upper limit to the luminosity and a lower limit to the amplitude of X-ray variability of SN 1998bw, respectively, due to the possible contribution of its host galaxy, a face-on spiral galaxy about one-tenth of the size of our Galaxy, which is only very marginally resolved in the *BeppoSAX* data. In fact, a galaxy of that type and size could easily account for almost all of the X-ray emission observed in 1998 November, when the flux was lowest (see, e.g., Fabbiano 1989).

The observed decay of S1 in the 2–10 keV band is well fitted by a power law $F(t) \propto t^{-p}$ with $p = 0.16 \pm 0.04$ (reduced $\chi^2 \simeq 0.7$). The fit with an exponential law $F(t) \propto e^{-t/\beta}$ with $\beta = 500 \pm 100$ days has a reduced $\chi^2$ of 2.4, corresponding to a probability of $\sim$10% for 2 degrees of freedom (dof), therefore not negligible (Fig. 7*b*). Both trends would be similar, considering the unknown dilution by the host galaxy of SN 1998bw, to the X-ray behavior of other supernovae (e.g., Kohmura et al. 1994; Zimmermann et al. 1994; Houck et al. 1998) and predicted by models of thermal bremsstrahlung of energetic electrons within the circumstellar medium (see, e.g., Chevalier & Fransson 1994; Chugai & Danziger 1994).

The prompt X-ray emission observed for SN 1998bw requires that the circumstellar medium be highly ionized (perhaps by the powerful explosion), to allow the X-rays to escape so soon after the explosion (see Zimmermann et al. 1994), and also very dense, as inferred also from the large radio output (Kulkarni et al. 1998a; Wieringa, Kulkarni, & Frail 1999). In these conditions, the X-rays might be produced by the reverse shock that results from the pressure of swept-up material on the outgoing shock and propagates back into the shocked supernova gas (Chevalier & Fransson 1994; Schlegel 1995). The temperature obtained from the thermal bremsstrahlung fit to the *BeppoSAX* LECS + MECS spectra, admittedly very poorly constrained, is compatible with that fitted to the medium or hard X-ray spectra of other supernovae (Kohmura et al. 1994; Leising et al. 1994; Dotani et al. 1987).

On the other hand, the mildly relativistic conditions evidently present in the expanding shock of SN 1998bw at early epochs (Kulkarni et al. 1998a) and the acceptable power-law fit obtained for the medium-energy X-ray spectra might suggest that nonthermal mechanisms are

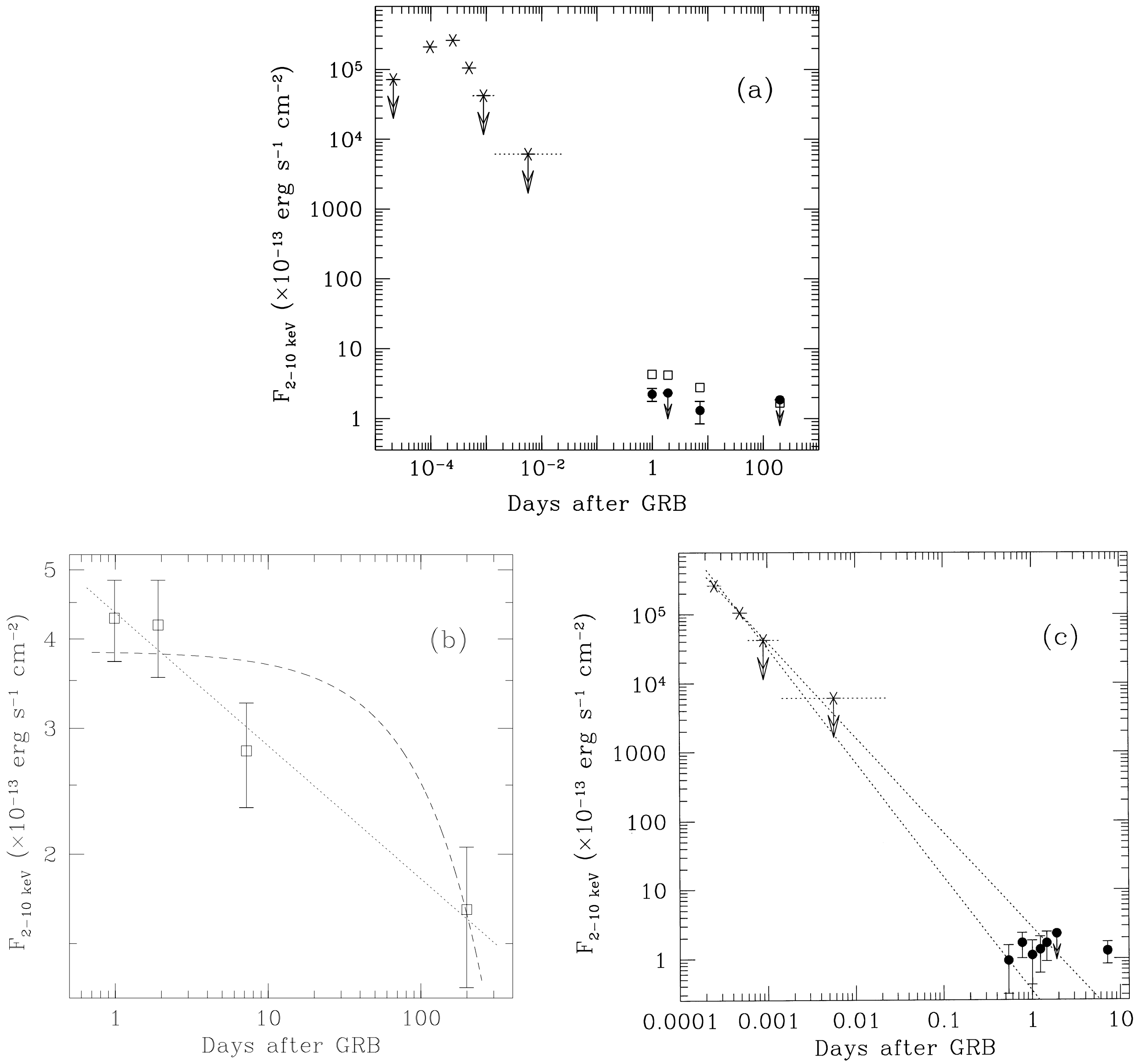


FIG. 7.—(*a*) *BeppoSAX* MECS light curves in the 2–10 keV band of the X-ray sources S1 (*open squares*) and S2 (*filled circles*) detected in the GRB 980425 field. The WFC early measurements and 3 $\sigma$ upper limits in the same band are also shown (*stars*). Uncertainties for the NFI measurements are 1 $\sigma$. The 1 $\sigma$ error bars for the WFC points are smaller than the symbol size and have not been reported. Horizontal dotted bars represent the time intervals on which the upper limits have been computed. (*b*) Same as (*a*) for source S1 only. The fits to the temporal decay with a power law of index $\sim$0.2 and with an exponential law of *e*-folding time $\sim$500 days are shown as dotted and dashed curves, respectively. (*c*) Same as (*a*) for source S2 only. The first NFI measurement of S2 in (*a*) is replaced here by 5 points obtained by integrating and averaging the flux in shorter time intervals. The dotted lines represent the power laws of indices $p \simeq 1.6$ and $p \simeq 1.4$ connecting the last WFC measurement and the first and last of the 5 NFI points of the April 26–27 light curve, respectively. The power laws are consistent with the WFC upper limits, and their extrapolations to the time of the third NFI observation (1998 May) fall below the lower bound of the data point, although they are compatible with it within $\gtrsim 2.5\ \sigma$.

responsible for the X-ray emission such as synchrotron radiation by the extremely energetic electrons, as was modeled for the radio emission by Li & Chevalier (1999), or inverse Compton scattering of relativistic electrons off optical/UV photons of the thermal ejecta (see Canizares, Kriss, & Feigelson 1982). The X-ray spectral index is consistent with that measured for the radio spectrum starting $\sim$15 days after the explosion (Kulkarni et al. 1998a; Wieringa et al. 1999) and with the slope connecting quasi-simultaneous radio and X-ray measurements ($\alpha \sim 0.8$). Therefore, it is difficult to establish whether the X-rays are produced through synchrotron or inverse Compton radiation. However, if inverse Compton losses were dominant, radio emission production would be rapidly inhibited (Schlegel 1995), contrary to the observations.

Assuming the X-rays have a synchrotron origin and adopting a single power law of index $\alpha \sim 0.8$ for the radio–to–X-ray synchrotron spectrum, we obtain a bolometric luminosity of $\sim 9 \times 10^{40}$ ergs s$^{-1}$. Assuming that the radio and X-ray–emitting regions are cospatial and expanding with a speed of $\sim 0.3c$ (Kulkarni et al. 1998a), we derive a magnetic field of $\lesssim 1$ G, similar to that found for SN 1980K by Canizares et al. (1982) assuming inverse Compton losses are responsible for the X-ray production.

However, the limited signal-to-noise ratio of the *BeppoSAX* spectra does not allow us to choose between synchrotron radiation and thermal bremsstrahlung as the mechanism for the medium-energy X-ray production.

The emission component detected in the softer part of the *BeppoSAX* spectrum, if fitted with a blackbody, has a temperature of $\sim 0.1$ keV, corresponding to a blackbody total luminosity of $\sim 10^{41}$ ergs $s^{-1}$. The inferred linear size of the emitting region is about one-third of the solar radius, too large for a compact object left as a remnant of the supernova explosion but approximately compatible with the size of the putative accretion disk promptly formed as a consequence of the "hypernova" or "collapsar" phenomenon, of which SN 1998bw might be an example (Paczyński 1998; MacFadyen & Woosley 1999; Woosley, Eastman, & Schmidt 1999). However, such a compact object or disk could be hardly visible at so early an epoch, because of the optical thickness of the material enshrouding it.

Blackbody soft X-ray emission is not expected from the supernova itself or from the expanding shell or ejecta, due to nonequilibrium conditions of the system. However, the occurrence of short ($\sim 1000$ s) thermal bursts at early times after a supernova explosion has been predicted, albeit at very soft energies, possibly even lower than those observable by the LECS (Schlegel 1995). We found no evidence in the LECS light curves of similar events, but the sampling is not conducive to that detection.

However, since there is no evidence of variability of the soft component in the long term, it might not be related to the supernova. In fact, its spectrum can be fitted also with a power law superimposed on, and steeper than, the one that describes the spectrum at higher energies. This suggests that the component might have a more complex spectrum (possibly extending toward ultraviolet wavelengths), of which a blackbody or steep power law is only an approximation. It could rather be a persistent (or slowly variable with a small amplitude) source of soft X-rays, such as the host galaxy itself, or just its bulge, or the superposition of unresolved X-ray sources within that galaxy, or diffuse hot gas, or the H II region in which SN 1998bw is located (Galama et al. 1998), or the underlying cluster DN 1931−529, or more probably, the sum of some or all of these contributions. The limited angular resolution of *BeppoSAX* does not allow us to disentangle this component from the supernova itself. Notwithstanding this possibility, we note that the unabsorbed luminosity in the 0.1–2 keV range, $5 \times 10^{40}$ ergs $s^{-1}$, given by the superposition of the fitted power-law and blackbody components, is similar to luminosities of supernovae observed in soft X-rays (Canizares et al. 1982; Bregman & Pildis 1992; Zimmermann et al. 1994; Schlegel, Petre, & Colbert 1996; Fabian & Terlevich 1996; Immler, Pietsch, & Aschenbach 1998b).

### 3.2. *The Association between GRB 980425 and SN 1998bw*

The GRB 980425 prompt event is relatively weak with respect to other GRBs, and rather soft. However, it has no outstanding features with respect to other *BeppoSAX* or BATSE GRBs, which might suggest a peculiar counterpart at longer wavelengths, such as a bright supernova, instead of a "classical" power-law fading afterglow. The $\sim 5$ s temporal lag between the WFC and the GRBM light curves could be due to a delay of X-ray emission during the burst with respect to the $\gamma$-rays or ascribed to intrinsic absorption in a medium becoming increasingly transparent (see, e.g., Böttcher et al. 1999). Similar soft lags from a few to $\sim 10$ s are observed also in other GRBs (Piro et al. 1998b, 1998c; Frontera et al. 2000).

If SN 1998bw is the counterpart of GRB 980425, the production of $\gamma$-rays could be accounted for by the explosion of the 14 $M_\odot$ helium core of a $\sim 35$ $M_\odot$ star (Woosley et al. 1999; MacFadyen & Woosley 1999) and by the subsequent expansion of a relativistic shock, in which nonthermal electrons are radiating photons of $\sim 100$ keV, provided the explosion is asymmetric, i.e., the GRB is produced in a relativistic jet (Iwamoto et al. 1998; Woosley et al. 1999; Höflich, Wheeler, & Wang 1999; Rej 1998; see, however, Kulkarni et al. 1998a). The presence of an undetectable, or barely detectable, nonthermal GRB remnant, underlying the brighter thermal supernova ejecta cannot be excluded (see, e.g., Iwamoto 1999).

Recent speculations have led to the proposal that every long ($>1$ s) GRB is formed via supernova, or hypernova, explosion (MacFadyen & Woosley 1999). The presence of a supernova underlying the GRB afterglow has been recently tested for the optical transients of some GRBs, with suggestive results (GRB 970228, Reichart 1999; Galama et al. 2000; GRB 970508, Germany et al. 2000; GRB 980326, Bloom et al. 1999; GRB 990510, Fruchter et al. 1999c; Beuermann et al. 1999; GRB 990712, Hjorth et al. 1999). Indeed, the recent discovery of a GRB optical counterpart at the intermediate redshift $z = 0.43$ (Galama et al. 1999c) might support a continuity of properties between GRB 980425 and the other precisely localized GRBs, perhaps based on the different amount of jet collimation (Woosley, MacFadyen, & Heger 2000) or different beaming, depending on the degree of jet alignment (Eichler & Levinson 1999; Cen 1998; Postnov, Prokhorov, & Lipunov 2000). In highly collimated or highly beamed GRBs, the nonthermal multiwavelength afterglow could overwhelm the underlying supernova emission. This should instead be detected more clearly in less collimated or less beamed (i.e., seen off-axis) GRBs, like GRB 980425, which are, or appear, weaker. Assuming association with SN 1998bw and isotropic emission, the total energy of GRB 980425 in the 40–700 keV, $\sim 5 \times 10^{47}$ ergs, is at least 4 orders of magnitude less than that of GRBs with known distance.

On the other hand, disregarding the fact that the probability of a chance coincidence of GRB 980425 and SN 1998bw is extremely low, one might consider S2 as the X-ray counterpart candidate of the burst. The possible detection of S2 in 1998 May 2–3, one week after the GRB, implies, with respect to the first NFI detection in April, a much slower decay than that normally observed for X-ray afterglows (e.g., Costa et al. 1997; Nicastro et al. 1998; Dal Fiume et al. 2000; in 't Zand et al. 1998; Nicastro et al. 1999; Vreeswijk et al. 1999; Heise et al. 1999).

Assuming a power-law decay between the X-ray flux measured by the WFC in the 2–10 keV range in the last $\sim 20$ s of the GRB and the flux measured in the first NFI observation (Fig. 7*a*), we derive a power-law index $p \sim 1.5$, which is consistent with the 3 $\sigma$ upper limits determined by the WFC in the 50–2000 s interval following the GRB and similar to that of other observed X-ray afterglows. If S2 is an afterglow, one would expect that its intraday variability followed this same temporal behavior. Therefore, we have binned the light curve of S2 in the first portion of the 1998 April pointing in five intervals of 20,000 s each. We have then connected with power laws the last WFC measurement with the first and last of these fluxes and have determined their indices to be $p \simeq 1.6$ and $p \simeq 1.4$ (Fig. 7*c*), respectively. The reduced $\chi^2$ values computed for these two power laws with respect to the remaining four NFI data points of April are 3 and 30, respectively, corresponding to low probabilities (1% and $\ll 1$) that the power laws describe the observed intrapointing light curve. (All points seem rather consistent with a constant trend.)

The upper limit derived for the second portion of the April pointing is inconclusive. However, the detection of S2 in 1998 May suggests a marginal deviation from the above power laws ($\gtrsim 2.5\ \sigma$). Therefore, the present data exclude at a confidence level of $\sim 99\%$, or higher, that S2 is an afterglow, unless a small rebursting, one week after the GRB, is superimposed to the power-law monotonic decline. This would be reminiscent of GRB 970508, although the timescales for rebursting occurrence and duration would be very different (Piro et al. 1998b).

## 4. CONCLUSION

Two previously unknown X-ray sources have been detected by the *BeppoSAX* NFIs in the field of GRB 980425. Neither of them has the obvious characteristics of an X-ray afterglow when compared with previously observed cases.

SN 1998bw is a very interesting candidate for further monitoring in the X-rays. Thanks to its rapid slew capability and to its wide energy range, *BeppoSAX* has promptly measured its spectrum up to energies beyond $\sim 5$ keV, where supernovae have so far been largely unexplored. Unfortunately, the signal is relatively modest (this is the second most distant supernova detected so far in the X-rays, after SN 1988Z, located at 95 Mpc, Fabian & Terlevich 1996), and therefore longer exposures and data of better signal-to-noise ratio are necessary to study in detail this source and its environment.

Concerning the identification of the X-ray counterpart of GRB 980425, our tentative conclusion is that S1 has a high probability of being associated with GRB 980425, while S2 is more probably a variable field source, albeit constant in the long term, like an active galaxy or a Galactic X-ray binary (we note that the probability of detecting by chance a source of the level of S2 is rather high, $\sim 10\%$; Cagnoni et al. 1998; Giommi et al. 1998). A spectroscopic survey of the NFI error box of S2 has been inconclusive in this respect (Halpern 1998). Observations of this field by an X-ray instrument with higher sensitivity (e.g., *XMM*) and spatial resolution (e.g., *Chandra*) than those attained by *BeppoSAX* might help elucidate this controversial issue.

We thank the *BeppoSAX* Mission Planning Team and the *BeppoSAX* SDC and Science Operation Center (SOC) personnel for help and support in the accomplishment of this project.

## APPENDIX

## ESTIMATE OF UPPER LIMITS AT THE 3 σ CONFIDENCE LEVEL

Suppose that $m$ counts are found in the region where the target is expected to appear and that in the same search area $b$ counts are expected from the background. If $m - b < 3\sqrt{b}$ we have no positive detection (at the 3 $\sigma$ confidence level) of the source and a 3 $\sigma$ upper limit is needed. We define the 3 $\sigma$ upper limit as the number $x$ that gives a probability to observe $m$ or fewer counts equal to the formal 3 $\sigma$ Gaussian probability, i.e.,

$$P(\leq m, x + b) = P_{\rm Gauss}(3\ \sigma)\ . \tag{A1}$$

Assuming Poisson statistics, equation (A1) becomes

$$e^{-(x+b)} \sum_{i=1}^{m} \frac{(x+b)}{i!} = 2.7 \times 10^{-3}\ . \tag{A2}$$

In the limit of large numbers equation (A2) reduces to

$$m = x + b - 3\sqrt{x+b}\ . \tag{A3}$$

By solving equation (A3) with respect to $x$ we have

$$x = \frac{9 + 2m + 3\sqrt{9 + 4m} - 2b}{2}\ .$$

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