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A COMPARATIVE STUDY OF THE X-RAY AFTERGLOW PROPERTIES OF OPTICALLY BRIGHT AND DARK GAMMA-RAY BURSTS

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ABSTRACT

We have examined the complete set of X-ray afterglow observations of dark and optically bright gamma-ray bursts (GRBs) performed by *BeppoSAX* through 2001 February. X-ray afterglows are detected in $\sim$90% of the cases. We do not find significant differences in the X-ray spectral shape, in particular no increased X-ray absorption in GRBs without optical transient (dark GRBs) compared to GRBs with optical transient (OTGRBs). Rather, we find that the 1.6–10 keV flux of OTGRBs is on average about 5 times larger than that of the dark GRBs. A Kolmogorov-Smirnov test shows that this difference is significant at 99.8% probability. Under the assumption that dark and OTGRBs have similar spectra, this could suggest that the first are uncaught in the optical band because they are just faint sources. In order to test this hypothesis, we have determined the optical–to–X-ray flux ratios of the sample. OTGRBs show a remarkably narrow distribution of flux ratios, which corresponds to an average optical–to–X-ray spectral index $\overline{\alpha}_{\rm oX}^{\rm OT} = 0.794 \pm 0.054$. We find that, while 75% of dark GRBs have flux ratio upper limits still consistent with those of OT GRBs, the remaining 25% are 4–10 times weaker in optical than in X-rays. The significance of this result is $\geq 2.6\ \sigma$. If this subpopulation of dark GRBs were constituted by objects assimilable to OTGRBs, they should have shown optical fluxes higher than upper limits actually found. We discuss the possible causes of their behavior, including a possible occurrence in high-density clouds or origin at very high redshift and a connection with ancient, Population III stars.

Subject heading: gamma rays: bursts

1. INTRODUCTION

About 50% of well-localized gamma-ray bursts (GRBs) show optical transients (OTs) successive to the prompt gamma-ray emission, whereas an X-ray counterpart is present in 90% of cases. It is possible that late and shallow observations could not detect the OTs in some cases; several authors argue that dim and/or rapidly decaying transients could bias the determination of the fraction of truly obscured GRBs (Fynbo et al. 2001a; Berger et al. 2001). However, recent reanalysis of optical observations (Reichart & Yost 2001; Ghisellini, Lazzati, & Covino 2000; Lazzati et al. 2002) has shown that GRBs without OT detection (usually dark GRBs, failed optical afterglows [FOAs], or gamma-ray bursts hiding an optical source transient [GHOSTs]) have had on average weaker optical counterparts, at least 2 mag in the *R* band, than GRBs with OTs. Therefore, they appear to constitute a different class of objects, albeit there could be a fraction undetected for bad imaging.

Two hypotheses have been put forward to explain the behavior of GHOSTs. First, they are similar to the other bright GRBs, except for the fact that their lines of sight pass through large and dusty molecular clouds that cause high absorption. Second, they are more distant than GRBs with OTs at $z \gtrsim 5$ (Fruchter 1999), so that the Lyman break is redshifted into the optical band. These GRBs might be associated with the explosion of ancient Population III, high-mass stars. Nevertheless, the distances of a few dark GRBs have been determined, and they do not imply high redshifts (Djorgovski et al. 2001b; Antonelli et al. 2000; Piro et al. 2002).

The goal of this paper is an analysis of a complete sample of *BeppoSAX* X-ray afterglows in order to distinguish between these various scenarios, including all X-ray fast observations from the launch to 2001 February. In § 2 and § 3 we present the data analysis of the afterglows and we show the results, whose implications are discussed in § 4. Finally, we summarize our conclusions in § 5.

2. DATA ANALYSIS

We have analyzed all 31 fast *BeppoSAX* observations of GRB X-ray afterglows taken by the Low Energy (0.1–10 keV) and Medium Energy (1.6–10 keV) Concentrator Spectrometer (LECS and MECS, respectively; see Parmar et al. 1997, Boella et al. 1997) up to GRB 010222. We excluded only GRB 960720 for the late follow up, GRB 990705 because of its high contamination of a nearby X-ray source, and GRB 980425 because of its peculiarity. X-ray follow up observations usually start $\sim$9–10 hr after the high-energy event and the typical observation time is $\sim 2 \times 10^5$ s for MECS and $\sim 5 \times 10^4$ s for LECS. The exposure—or integration—lasts $\sim 1/3$ of the observation.

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In order to find out the GRB X-ray afterglows, we first built up the images of each GRB with the MECS and selected sources with 3 σ significance within the WFC error box.[9] Next, we built the light curves of these sources to recognize afterglows through their typical fading emission. The counts were collected within a circle centered on source with radius $r = 4'$. Then we subtracted the background collected in annuli around the extraction area and 5 times more extended. Local backgrounds were used in order to take into account possible time fluctuations. ToOs after the first one (typically $\sim$2 days after) have been used, if available. We have fitted the light curves with a simple power law $N_{\rm cts} \propto t^{-\delta}$ (where $N_{\rm cts}$ is counts per second), and 26 sources with decaying index $\delta > 0$ (at 90% confidence level) have been recognized as GRB afterglows. In the case of GRB 970111, GRB 991106, and GRB 000615, we have detected one source within the WFC error box that does not show a significant fading behavior. We will refer to them as "candidate" afterglows.[10] We have calculated the probability of having serendipitous sources with flux within the WFC error box, adopting the log N–log S distribution for *BeppoSAX* released by Giommi, Perri, & Fiore (2000). The probability is 0.027 for each one, while the probability that all of them are not afterglows is $P \sim 10^{-5}$.

The MECS integration time for GRB 990907 was only 1070 s, so the presence of a fading flux could not be verified. The X-ray source detected was recognized as the GRB afterglow because the probability of having a serendipitous source with flux 10^{-12} ergs cm^{-2} s^{-1} (see below) in the WFC error box was $\simeq$0.007. Finally, in the case of GRB 990217 and GRB 010220, we have not detected any source with 3 σ significance.

To obtain flux, we have produced spectra for the afterglows from LECS and MECS first ToO data. For absorption and spectral index, we have selected those with more than 150 photons in the MECS (background subtracted). Five GHOSTs and nine OTGRBs passed this criterion.

We have generally taken the LECS data between 0.1 and 4.0 keV and the MECS data between 1.6 and 10 keV. The backgrounds we have used are the library ones because they have a very good signal-to-noise ratio, because of long exposure times.[11] However, we have taken the minimum energy for LECS to be 0.4 keV if the Galactic column density was $N_{\rm H} \geq 5 \times 10^{20}$ cm^{-2} because in this case the low-energy backgrounds differ from the library ones, which have been taken at high Galactic latitudes and lower column densities (Stratta et al. 2003). If we had not adopted this criterion, our analysis would have led to overestimate the true absorption at the source.

The standard spectrum model to fit the data consists of a constant, Galactic absorption, extragalactic absorption (i.e., in situ) and a power law. The constant has been included because LECS and MECS observe a decaying source at different times. Its value is allowed to vary within a range, obtained in each case by fitting LECS and MECS data in the 1.6–4 keV interval (to avoid absorption effects) with a simple power-law model. The redshift in our fits has been forced to be 1 for all bursts. This value corresponds roughly to the average redshift of OTGRBs. We have adopted this "working hypothesis" to obtain a homogeneous set that allows us to compare the absorption properties of dark GRBs in the assumption that they are at the same distance.

We have calculated the 1.6–10 keV flux of dark and bright GRBs 11 hr after the burst trigger. We have chosen this time to avoid effects of changes in decaying slope. The average count rate in the MECS has been associated with the flux given by the spectrum. Successively, we have taken the count rate at 11 hr, which is given by light curves, to compute the flux at that time. In most cases, observations include it. In a few cases (e.g., GRB 000926) the flux has been extrapolated.

For GRB 990907, the counts collected were very few, and we have not been able to do any spectral analysis. We estimated the flux assuming a spectral index $\alpha = 1.05$. For the two nondetections, we calculated the 3 σ upper limits on counts and converted them to flux adopting again $\alpha = 1.05$. In all successive analysis, upper limits have been included as true afterglows as well as candidate afterglows.

As a first assessment of our study, we can say that X-ray afterglows follow the prompt gamma emission in 26 of 31 cases, which constitute 84% of the sample. If all doubtful sources are considered as afterglows, then the fraction of X-ray afterglows increases up to 94%. Instead, optical afterglows are 11 and constitute only 37% of the sample.[12] We note that all these fractions are in agreement with published data.

We do not know any optical study on GRB 980515. We calculated its X-ray flux, but this burst has not been included in our successive analysis.

3. THE X-RAY SPECTRAL AND FLUX PROPERTIES

The data we have obtained are the result of the convolution of the intrinsic distribution with the measurement error distribution. Under the assumption that both are Gaussian, it is possible to deconvolve the two distributions. We have followed a maximum likelihood method (Maccacaro et al. 1988) to gather jointly the best estimates of parent distribution mean and standard deviation. We have used these best estimates (hereafter indicated with index m) for successive analysis, but we have calculated and shown also the weighted mean and standard deviation of our data. The complete set of fit parameters is given in Table 1 and plotted in Figures 1 and 2.

For GHOSTs, the weighted mean and the standard deviation of the measured energy indexes are $\alpha = 1.3 \pm 0.18$ (hereafter errors are at 1 σ unless otherwise indicated) and $\sigma = 0.31$, respectively. The best estimates for the parent population are $\alpha^m = 1.3^{+0.27}_{-0.26}$, $\sigma^m = 0^{+0.37}$.[13] In the case of OTGRBs, $\alpha = 1.04 \pm 0.03$, $\sigma = 0.44$ and $\alpha^m = 1.05^{+0.11}_{-0.06}$, $\sigma^m = 0.05^{+0.13}_{-0.05}$ for the observed and the parent distribution, respectively. Energy indexes of dark and optically bright burst are compatible at the 1 σ level.

[9] IPN error box for GRB 000926 (Hurley et al. 2000), ASM error box for GRB 980703 (Levine et al. 1998).

[10] In the case of GRB 991106, the source in the WFC error box could be a type I Galactic X-ray burst (Cornelisse et al. 2002).

[11] In the case of GRB 970111, 970402, and 991014, the use of local background enabled us to gather better results.

[12] GRB 980515 has not been included in this calculation; see further.

[13] In a few cases, the best estimates of the standard deviation in the parent population are equal to or compatible with zero. This suggests that measurements are dominated by experimental errors.

TABLE 1

GRB X-Ray and Optical Density Flux, Spectral Index α, Absorption at $z = 1$, and Optical–to–X-Ray Flux Ratio

GRB	X-Ray Flux (10^{-13} ergs cm^{-2} s^{-1})	α	$N_{\rm H}$ (10^{22} cm^{-2})	$f_{\rm OX}$[a]	Optical Flux (μJy)
Dark GRBs					
970111	1.11 ± 0.35[b]			$\leq$27.4	$\leq$30.4
970402	2.62 ± 1.31			$\leq$7.82	$\leq$20.5
971227	$3.24^{+1.59}_{-2.08}$			$\leq$1.5	$\leq$4.87
980515	$2.01^{+0.54}_{-0.93}$				
981226	$4.88^{+0.4}_{-0.73}$			$\leq$0.32	$\leq$1.56
990217	$\leq$1.11[c]			$\leq$1.6	$\leq$1.77
990627	$1.87^{+0.83}_{-1.08}$			$\leq$16.9	$\leq$31.6
990704	$5.95^{+1.29}_{-1.29}$	$1.75^{1.09}_{-0.59}$	$4.83^{+10.37}_{-3.57}$	$\leq$0.2	$\leq$1.19
990806	3.8 ± 1.03	$1.56^{+1.03}_{-0.71}$	$3.16^{+10.64}_{-3.09}$	$\leq$0.4	$\leq$1.5
990907	10.2 ± 5.6			$\leq$0.78	$\leq$8
991014	$4.01^{+1.37}_{-1.2}$			$\leq$0.89	$\leq$3.6
991106	2.09 ± 1.08[b]			$\leq$12.6	$\leq$26.3
000210	$3.69^{+1.02}_{-1.08}$	$1.67^{+1.01}_{-.78}$	$2.95^{+6.3}_{-2.27}$	$\leq$0.52	$\leq$1.92
000214	$6.37^{+1.98}_{-1.77}$	$1.18 \pm .43$	$0^{+0.71}$	$\leq$7.59	$\leq$48.4
000528	2.33 ± 1.04			$\leq$1.31	$\leq$3.05
000529	$3.55^{+1.24}_{-2.16}$			$\leq$11.91	$\leq$42.3
000615	1.28 ± 0.33[b]			$\leq$2.04	$\leq$2.61
001109	$20^{+5.8}_{-4.6}$	$1.26^{+0.12}_{-0.49}$	$2.83^{+4.7}_{-2.83}$	$\leq$0.59	$\leq$11.81
010214	$2.67^{+0.93}_{-1.25}$			$\leq$1.89	$\leq$5
010220	< 1.63[c]			$\leq$14.5	$\leq$23.2
OT GRBs					
970228	19.7 ± 3.3	$0.8^{+0.3}_{-0.37}$	$0.83^{+1.51}_{-0.83}$	2.2	$43.8^{+5.5}_{-4.9}$
970508	7.91 ± 0.67	$1.14^{+0.51}_{-0.36}$	$0.53^{+1.87}_{-0.53}$	1.26	$9.6^{+0.74}_{-0.71}$
971214	6.03 ± 1.09	$0.98^{+0.44}_{-0.56}$	$2.98^{+6.51}_{-2.98}$	0.86	5.2 ± 0.56
980329	5.99 ± 0.93	$1.42^{+0.58}_{-0.39}$	$0.21^{+4.05}_{-0.21}$	0.67	$4^{+2.4}_{-1.3}$
980519	3.97 ± 0.92	$2.2^{+1.55}_{-1.09}$	$3.2^{+11.5}_{-3.2}$	20.6	$82^{+10.4}_{-9.2}$
980613	2.14 ± 0.86			1.14	$2.4^{+2.4}_{-1.2}$
980703	$15.6^{+7.7}_{-5.6}$	$1.77^{+.60}_{-.47}$	$2.88^{+4.74}_{-2.06}$	4.34	67.7 ± 28.8
990123	53 ± 2	$0.99^{+0.07}_{-0.08}$	$0.09^{+0.11}_{-0.05}$	0.92	40.33 ± 0.93
990510	36.7 ± 2.8	1.19 ± 0.14	$0.21^{+0.61}_{-0.21}$	4.44	163 ± 15.6
000926	$39.6^{+22.4}_{-19.1}$			3.94	156.9 ± 9
010222	68 ± 4.2	1 ± 0.1	$0.53^{+0.42}_{-0.27}$	0.74	50.6 ± 2.3

Note.—Errors at 90% confidence level.

[a] Obtained dividing the R-band flux (or upper limits) in μ Jy by the 1.6–10 keV X-ray flux in 10^{-13} cgs.

[b] Candidate afterglow.

[c] 3 σ upper limit.

The mean value and the standard (linear) deviation of the measured absorption (hereafter in units of 10^{22} cm^{-2}) are, respectively, $N_{\rm H} = 0.13^{+0.42}_{-0.13}$, $\sigma = 3.05$ for dark GRBs, and $N_{\rm H} = 0.13 \pm 0.06$, $\sigma = 1.7$ for OTGRBs. The best estimates for the parent population are $N^m_{\rm H} = 0.14^{+1.46}_{-0.14}$, $\sigma^m = 0^{+1.58}$ for dark GRBs, and $N^m_{\rm H} = 0.13^{+0.13}_{-0.075}$, $\sigma^m = 0^{+0.35}$ (see also Stratta et al. 2003) for OTGRBs. *The amount of absorption does not appear statistically different for optically bright and dark GRBs in the assumption that they lie at the same average z.*

The logarithmic weighted means and the standard deviations of the observed X-ray fluxes (cgs units) are $\langle \log F \rangle = -12.38 \pm 0.02$, $\sigma = 0.34$ for dark GRBs, and $\langle \log F \rangle = -11.45 \pm 0.01$, $\sigma = 0.65$ for OTGRBs. Best estimates for the parent population are $\langle \log F \rangle^m = -12.53^{+0.11}_{-0.09}$, $\sigma^m = 0.23^{+0.09}_{-0.05}$ for dark GRBs and $\langle \log F \rangle^m = -11.85^{+0.22}_{-0.23}$, $\sigma^m = 0.47^{+0.2}_{-0.12}$ for GRBs with OTs. The GHOST mean flux is likely overestimated, because we have considered upper limits as detections.

The logarithmic ratio between the mean fluxes of the two parent populations is 0.68 ± 0.25, which corresponds to 4.8 in linear units. A Kolmogorov-Smirnov (K-S) test performed on the flux distributions shows that the probability that optically bright and dark GRBs derive from the same population is $P = 2 \times 10^{-3}$. This is a conservative result, because it has been obtained by including the upper limits and the nonfading sources as true afterglows in the set of dark GRBs. If we were to substitute the nonfading source fluxes with the 3 σ upper limits of their WFC error boxes, then the distributions of dark and optically bright GRBs would be even more different because limits are lower.

4. DISCUSSION

Our analysis shows that dark GRBs have on average weaker X-ray flux than bright GRBs. Then, we could simply explain why we miss their optical detection by assuming that dark bursts are weaker than OT GRBs in the optical band by the same ratio. Dark bursts should have had OTs at least

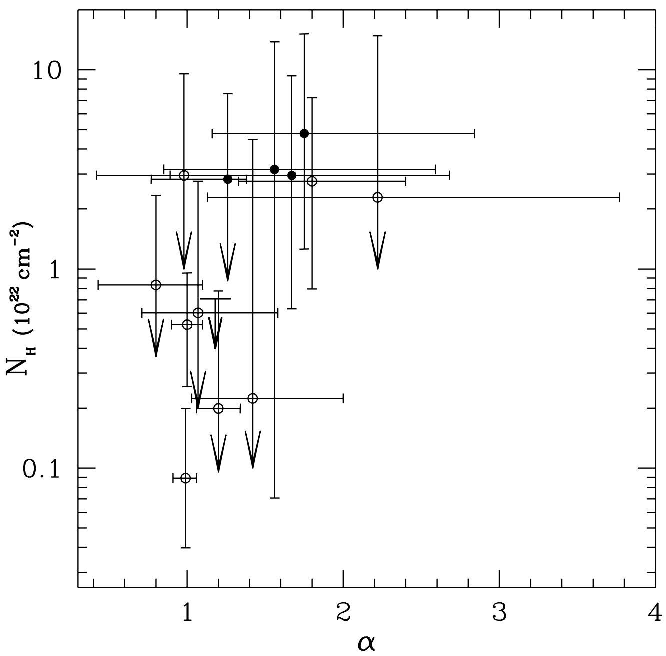

FIG. 1.—N_H vs. spectral index of high-statistic GRBs. *Filled circles*: dark GRBs. *Open circles*: OTGRBs.

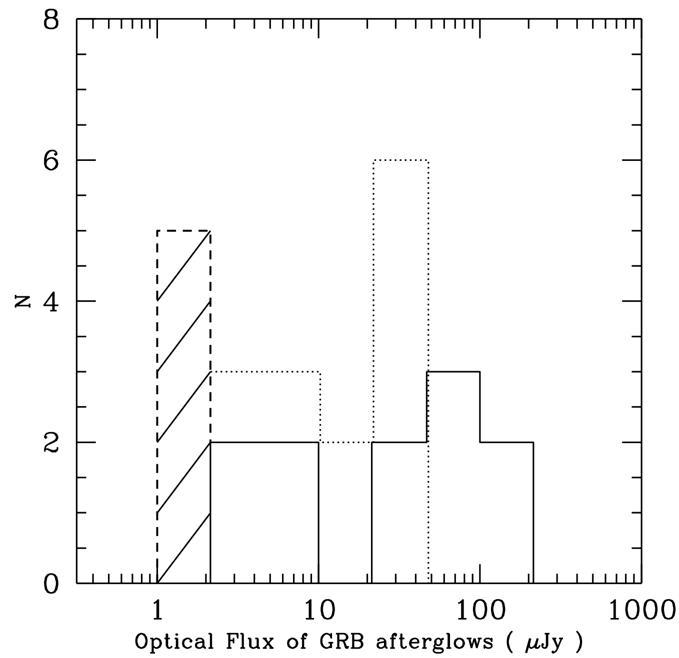

FIG. 3.—Histogram of all the GRB optical fluxes and upper limits 11 hr after the burst. *Solid line*: OTGRBs. *Dotted line*: GHOST upper limits. *Short-dashed line*: The most obscure GHOSTs.

2 mag fainter than OT GRBs; the 4.8 flux ratio that we have found corresponds to $\simeq$1.7 mag.

In order to check the viability of this hypothesis, we have calculated the optical flux density in the *R* band and hence the optical–to–X-ray flux ratios (f_{oX}) of each OTGRB and GHOST 11 hr after the burst (Lazzati et al. 2002, Fynbo et al. 2001a and reference therein, 2001b, 2001c; Galama et al. 1998; Hjorth et al. 2002; Vreeswijk et al. 1999; Stanek et al. 1999; Gal et al. 1999; Masetti et al. 2001; Greiner et al. 2000; Rol & Mandel 2001; Berger et al. 2002). Upper limits on optical fluxes of GHOSTs have been extrapolated from the tightest constraint available and adopting an optical flux decaying index $\delta = -1.15$. Our data are corrected for Galactic extinction, which has been calculated by converting (Zombeck 1990) the Galactic absorption given by Dickey & Lockman (1990). Results are shown in Table 1 and plotted in Figures 3, 4, and 5. We note that the optical and X-ray fluxes of OTGRBs *are correlated:* the higher the

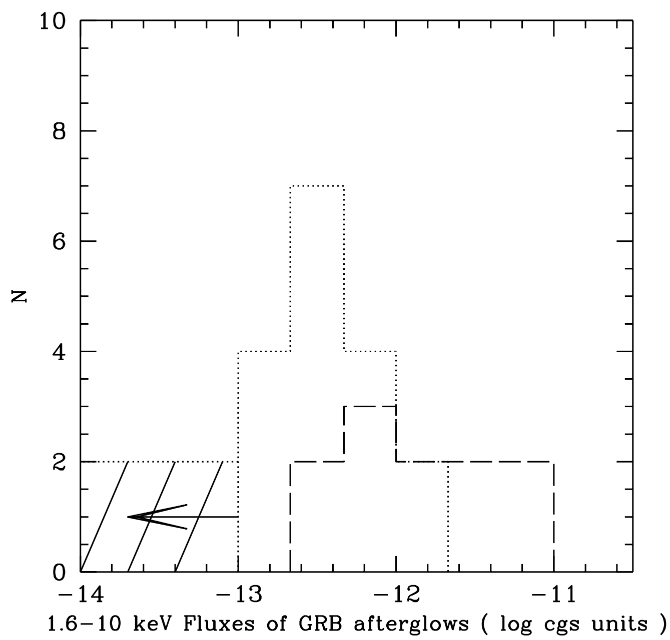

FIG. 2.—Histogram of 1.6–10 keV fluxes of GRBs 11 hr after the burst. *Long-dashed line*: OT GRBs. *Dotted line*: dark GRBs, candidate afterglows included. The arrow indicates the two upper limits set $\equiv 10^{-13}$ in order to clarify the picture.

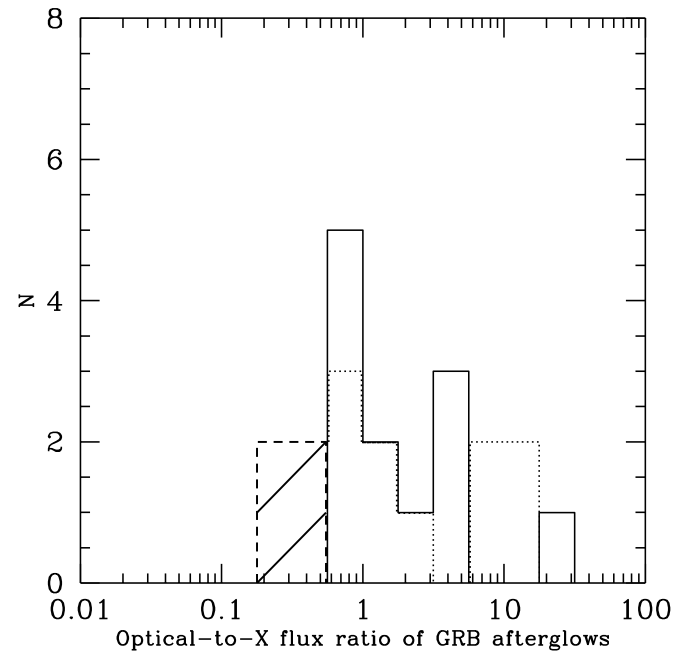

FIG. 4.—Optical–to–X-ray flux ratios. *Dotted lines*: Dark GRB upper limits. *Short-dashed line*: The most obscure dark GRBs. *Solid line*: OTGRBs. Nondetected X-ray afterglows are not shown.

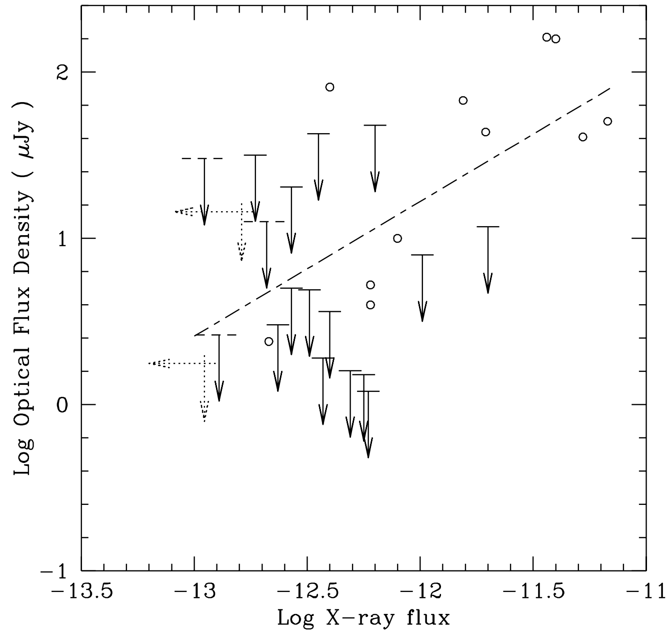

FIG. 5.—X-ray vs. optical flux of GHOSTs and OTGRBs. *Open circles*: OTGRBs. *Solid arrows*: GHOSTs. *Dashed arrows*: Candidate sources. *Dotted arrows*: Upper limits. *Short-long dashed line*: Best fit of optical vs. X-ray flux for OTGRBs, GRB 980519 included.

X-ray flux, the more luminous is the optical counterpart. The probability that it occurs by chance is only ~1.5%. The logarithmic standard deviation of $f_{\rm oX}$ is $\sigma^m_{f_{\rm oX}} = 0.42^{+0.2}_{-0.12}$, which corresponds to a multiplicative factor of 2.6, while the logarithmic mean is $\langle \log f^{\rm OT}_{\rm oX} \rangle^m = 0.3 \pm 0.22$ if the X-ray and optical fluxes are expressed in 10^{-13} ergs cm^{-2} s^{-1} and μJy, respectively. We have fitted the distribution of X-ray and optical fluxes with the function $\log F_{\rm optical} = K + A \log F_{1.6-10\,{\rm keV}}$. The best-fit values are $A = 0.81$, $K = 0.41$. We have also calculated the average optical–to–X-ray spectral index, $\overline{\alpha}_{\rm oX}$, as a function of $\langle \log f^{\rm OT}_{\rm oX} \rangle^m$, by adopting the X-ray and optical density flux at 2 keV and *R* band, respectively, and X-ray spectral index $\alpha_{\rm X} = 1.05$. Our result is $\overline{\alpha}^{\rm OT}_{\rm oX} = 0.79 \pm 0.054$.

If we exclude GRB 980519, which seems to be the only afterglow explained by interaction of a jet outflow with a star wind medium (Jaunsen et al. 2001), the correlation is strengthened: $\sigma^m_{f_{\rm oX}} = 0.28^{+0.14}_{-0.08}$, which corresponds to a multiplicative factor of 1.9; the probability of a chance occurrence is <0.001; $\langle \log f^{\rm OT}_{\rm oX} \rangle^m = 0.18^{+0.16}_{-0.14}$. The best-fit values are $A = 0.91$ and $K = 0.24$.

We can immediately recognize that 75% of the GHOSTs of our sample (14 of 19) have optical flux upper limits consistent with OT detections (see Fig. 3), so they may not be actually "dark." Optical follow-ups conducted for these bursts would not have been deep enough to detect the faintest OTs in our set. A similar fraction has been found out by Fynbo et al. (2001a) and Berger et al. (2002), comparing sets of nondetections with the light curves of the dim afterglows of GRB 000630 and GRB 020124. It is worth noting that the $f_{\rm oX}$ upper limits of these 14 objects are quite similar to OTGRBs ones: a K-S test performed shows that the probability they belong to the same population is not marginal.[14] This fact gives support to the fact that they could be faint sources with optical properties assimilable to X-ray ones.

The remaining five objects, which constitute 25% of GHOSTs, have optical flux upper limits lower than all OTGRBs in our set (see Fig. 3). Furthermore, their optical emission must have been even 2–3 times fainter than the dim afterglow of GRB 000630 and 4–6 fainter than GRB 020124, which had an *R*-band flux $F^R_{11\,{\rm hr}} \simeq 3.4\ \mu$Jy and $F^R_{11\,{\rm hr}} \simeq 7.9\ \mu$Jy, respectively.[15] These two optical afterglows, however, are not the weakest ever occurred. In our set, the OT of GRB 980613 is even dimmer (see Table 1) and establishes a more stringent test.

We wonder if the hypothesis of weaker flux at all wavelengths can hold for these 5 GHOSTs (hereafter we refer to them as the "darkest" or the "most obscured," etc., for simplicity). If so, we would expect that their X-ray fluxes were proportionally very weak like the optical fluxes, so their $f_{\rm oX}$ values should be not very different from OTGRBs. In 4 cases of 5 the $f_{\rm oX}$ values are lower than all OTGRBs and 4–10 times lower than the average optical–to–X-ray flux ratio of OTGRBs. The exception is GRB 990217, which has upper limits both in optical and in X-rays flux. If we use both of them, then we get $\log f_{\rm oX} = 0.2$, which is much more similar to $\langle \log f^{\rm OT}_{\rm oX} \rangle^m$. We have performed a K-S test on $f_{\rm oX}$ between all these darkest bursts and all OTGRBs. The probability that they are drawn from the same distribution is $P \leq 0.01$ ($\geq 2.6\ \sigma$ confidence level). The average optical–to–X-ray spectral index of these objects $\overline{\alpha}_{\rm oX} \leq 0.62$, well below that of OTGRBs. Therefore, we have a strong indication that for these bursts the spectrum is depleted in the optical band, by ~2 mag on average.

The X-ray mean flux of these 5 GHOSTs is -12.48 ± 0.16. The logarithmic ratio between the OTGRB X-ray flux mean and this mean is $\log r = 0.63 \pm 0.28$, which corresponds to a factor of 4.3. A hypothesis for the absence of OTs and fainter X-ray flux is that of very high redshift. The GRB prompt emission and X-ray afterglow of the strongest bursts (e.g., GRB 990123 and GRB 990510) could be detectable even they occur at $z > 10$ (Lamb & Reichart 2003). However, if GHOSTs were at $z \gtrsim 5$, then extragalactic hydrogen clouds would entirely wash out optical emission (Piro 2002; Fruchter 1999; Becker et al. 2001).

To estimate the average redshift of the most obscure GRBs, we use the formula (Lamb & Reichart 2003)

$$F(\nu, t) = \frac{L_\nu(\nu, t)}{4\pi D^2(z)(1+z)^{1-\alpha+\delta}} , \quad (1)$$

where α is the spectral index, δ is the decaying (temporal) index and $D(z)$ is the comoving distance. We assume the cosmological parameters values $H_0 = 65$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$. The average of the known redshifts of OTGRBs in our set is $\overline{z}_{\rm OT} \simeq 1.5$.

In the simplest model of GRB afterglows, $\delta = -4/3$, $\alpha = 2\delta/3$, so $1 - \alpha + \delta = 5/9$. For such parameters, the average redshift of the darkest GRBs should be $2.6 \leq \overline{z}_D \leq 8.7$ under the assumption that the lower mean flux were only due to their larger distances and not to an intrinsic difference in their luminosity. Using the best estimate of $\alpha = 1.05$ calculated for OTGRBs and the average $\delta = 1.33$ of the strongest bursts of our sample, we obtain

[14] GRB 010220 has limits on optical and X-ray flux, so its $f_{\rm oX}$ is not constrained. However, wherever it is, it would not affect much the result.

[15] Data extrapolated with best fit values given by the authors and corrected for Galactic extinction.

$2.3 \leq \bar{z}_D \leq 7.8$. We should also expect a distribution of burst redshifts around $\bar{z}_D$. These facts make the high-redshift scenario for the most obscure GHOSTs still plausible.

Adopting the hypothesis, GRBs are the final result of very massive star evolution, an interesting issue to address is what might be the progenitors of GRBs at very high redshifts. Currently, we observe only old and low-mass Population II stars, but even high-mass stars could have formed. Theories suggest that the first stars of the universe—the so-called Population III—might have very large mass, so they could possibly be good candidates. Recent calculations suggest (Lamb & Reichart 2000; Valageas & Silk 1999; Gnedin & Ostriker 1997; Ostriker & Gnedin 1996) that the star formation rate has two peaks. The first one, at $20 \gtrsim z \gtrsim 16$ is due to Population III stars. The second one, due to Population II, is higher and much broader and it is at a redshift in the range $12 \gtrsim z \gtrsim 2$. Also the number of stars (i.e., the star formation rate time-dilated and weighted by the comoving volume of the universe) shows two peaks at $z \sim 8$ and $z \sim 2$.

In a few cases, however, the redshifts of some dark GRBs have been almost securely found, e.g., GRB 970828 at $z = 1$ (Djorgovski et al. 2001b), GRB 000210 at $z = 0.85$ (Piro et al. 2002), GRB 000214 at $z = 0.44$ (Antonelli et al. 2000), while GRB 981226 is also likely to have not occurred at very high redshift (Frail et al. 1999), because the candidate host galaxy is still detected in the R band. With present statistics, at least ~15% of the examined dark GRBs are not at very large redshift. It should be noticed that two of them are included in the list of most obscure objects in our set.

A hypothesis to explain the lack of the optical emission, an alternative to the very high redshift scenario, may be strong absorption (Djorgovski et al. 2001a). So far, we have collected many indications that GRBs take place in dense environments, like the giant molecular clouds (hereafter GMCs) (Piro 2002). GMCs are very rich in dust, which extinguishes very efficiently the optical and UV light. Piro et al. (2002) argue that in the case of GRB 000210 the lower limit on amount of obscuration is 1.6 mag in the R band. This value has been obtained extrapolating a power-law spectrum, described by the fireball model, from the X-ray band to the optical band and comparing the expected flux with the upper limits. We find a similar result through our model-independent analysis of optical–to–X-ray flux ratios. The $f_{\rm oX}$ upper limits of the burst is 3.8 times lower than the average value of $f_{\rm oX}$ for OTGRBs, which corresponds to $\gtrsim 1.5$ mag depletion. The measurements of *Chandra* X-ray Observatory showed that the amount of local absorption is able to explain this obscuration, under the assumption that the dust-to-gas ratio of the intervening medium is the same of the Galaxy or higher. Similarly, Djorgovski et al. (2001b) derived extinction in the case of GHOST GRB 970828 (Yoshida et al. 2001), for which a significative amount of X-ray absorption was detected. However, we note that in the case of OTGRBs the dust-to-gas ratio seems not to be consistent with the Galactic one (Stratta et al. 2003; Galama & Wijers 2001).

If the most obscure GHOSTs were similar to GRBs with OT except for higher absorption, we would expect to see differences in values of $N_{\rm H}$. From our results, we cannot affirm that $N_{\rm H}$ in these bursts shows this tendency, also because of considerable errors (see Table 1 and Figure 1). For those with good statistics, we do not find any absorption value 3 σ higher than the Galactic value but marginal evidence (~2 σ). On the other hand, we cannot rule out the hypothesis of obscuring GMCs altogether. The upper limits on $N_{\rm H}$, a few $\times 10^{22}$, are in fact the typical column densities of GMCs. *The optical absorption, however, does not imply that most obscure GHOSTs have X-ray flux weaker than OTGRBs, as we have found in our analysis,* because X-ray absorption is almost negligible at energy larger than 1.6 keV. Reichart & Yost (2003) try to reconcile this fact with the hypothesis of dusty birthplaces for GRBs and, in particular, they considered the effect of variously beamed GRB fireballs on their dusty environments. The energetics of GRBs are more or less the same for all events (Frail et al. 2001), but the beaming angles differ, being narrower for stronger bursts. The larger the beaming angle is, the more difficult it is for prompt UV and X-ray emission to destroy dust along the line of sight (Waxman & Draine 2000; Fruchter, Krolik, & Rhoads 2001; Draine & Hao 2002; Perna & Lazzati 2002), so that we see weak GRBs without OT. With a narrower beaming angle, the prompt emission will destroy a larger fraction of dust and the GRBs will appear strong and with OT. If this hypothesis is correct, on the basis of our results we have to assume that the average beaming angle of the darkest GHOSTs is ~2 times wider than the OTGRB one. According to Frail et al., the average beaming angle of *BeppoSAX* OT GRBs is $\theta \sim 0.1$ rad, so that the average beaming angle of the darkest GRBs should be $\theta \sim 0.2$ rad. This prediction is important, because it can be experimentally tested by observing and timing the presence of achromatic breaks in the light curves.

Another consequence of dark GRB occurrence in high-density environments should be the detection of semi-ionized absorber in the low-energy X-ray spectrum. So far, this kind of feature has not been found. The ionization front, however, should be rather sharp (see, e.g., Draine & Hao 2002), and therefore it would be hard to detect signatures of semi-ionized species in the X-ray spectra of the bursts.

5. CONCLUSIONS

We have discussed the issue of GRBs with X-ray but no optical afterglows. We have performed a standard temporal and spectral analysis of a complete sample of 31 GRB X-ray follow-up observations of *BeppoSAX*, i.e., all the fast observations from the launch until 2001 February. We have found that X-ray afterglows follow the prompt gamma emission in 84%–94% of the cases.

We have obtained the 1.6–10 keV fluxes 11 hr after the trigger for each GRB and the values of $N_{\rm H}$ at $z = 1$ to compare the absorption properties for strong X-ray afterglows. While absorption of optically bright and dark GRBs does not appear to be significantly different, the fluxes of GRBs with OT are on average about 5 times stronger than GHOST ones. The probability that GHOSTs and optically bright GRBs belong to the same population in fluxes is ≤ 0.002.

From the very fact that X-ray fluxes of dark GRBs are 5 times lower than that of OTGRBs, the optical fluxes could be ~2 mag lower under the assumption that the shape of the optical–to–X-ray spectrum is the same as that of OTGRBs. This difference could explain the nondetection of the optical transient. In order to test this hypothesis, we have calculated the optical–to–X-ray flux ratios of OTGRBs and upper limits for GHOSTs. OTGRBs show a tight correlation of optical and X-ray fluxes. The mean for OTGRBs is $\langle \log f_{\rm oX}^{\rm OT} \rangle^m = 0.3 \pm 0.22$ and $\sigma^m_{f_{\rm oX}} = 0.4$; the probability of a chance correlation is a marginal ∼1%. We find that 75% of GHOSTs have f_{oX} upper limits similar to OTGRB ones; however, the remaining ∼25% of dark bursts are fainter in optical than in X-rays, being their average optical–to–X-ray flux ratio $\langle \log f_{oX} \rangle^m \leq -0.4$. Thus, we have a strong indication that for these bursts the spectra are different from OTGRBs. This result is significant at $\geq 2.6\,\sigma$ level.

Two different interpretations for this effect can be given: (1) location at $z > 5$, and (2) higher absorption. In the very high redshift scenario, the optical flux of the sample is extinguished by the intervening Lyα systems, while the X-ray flux lower than OTGRBs is understood in terms of a higher distance.

However, given the fact that some GHOSTs of the sample almost certainly do not lie at very high redshift, we have considered the alternative possibility of occurrence in dusty and dense environments like GMCs. We have not found that these bursts to have a higher absorption than optically bright GRBs, but we note that upper limits on N_H are consistent with those of giant clouds. In the case of GRB 000210 our model-independent analysis has shown a depletion in the optical, which is compatible with the X-ray absorption measured by *Chandra*, assuming a gas-to-dust ratio similar to that of our Galaxy.

In the near future, a key role will be played by fast and deep follow-up X-ray and optical observations of GRBs, which will allow us to constrain better their spectral properties. In particular, observations in the IR band are a very important tool because they are less sensitive to dust and to Lyα extinction. They will enable us to investigate dark GRB properties like distance, which is a crucial piece of information to disclose the nature of these objects.

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