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DARK GAMMA-RAY BURSTS IN THE SWIFT ERA

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ABSTRACT

We present an optical flux vs. optical-to-X-ray spectral index ($\beta_{\rm OX}$) diagram for all known gamma-ray bursts (GRBs) for which an X-ray afterglow has been detected. We propose an operational definition of optically dark bursts as those bursts in the diagram that are both faint ($R > 23$ after 11 h) and subluminous with respect to the fireball model ($\beta_{\rm OX} < 0.5$). Out of a sample of 52 GRBs we identify 5 dark bursts. The diagram serves as a simple and quick diagnostic tool for identifying dark GRBs based on limited information, particularly useful for early and objective identification of dark Swift GRBs.

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

1. INTRODUCTION

Dark gamma-ray bursts (GRBs) remain one of the unresolved issues in GRB research. Shortly after the localization of the first GRB afterglows it became clear that not all GRBs were accompanied by detections of optical afterglows (OAs). In fact, a fairly large fraction, about 60–70% of well localized GRBs did not lead to detections at optical wavelengths (Fynbo et al. 2001b; Lazzati, Covino & Ghisellini 2002).

Various explanations have been put forward in order to shed light on dark bursts. The *obscuration scenario* (e.g., Groot et al. 1998; Taylor et al. 1998) ascribes the failed OA detection to extinction. Although there is evidence from X-rays (Galama & Wijers 2001) and damped Lyα absorbers (e.g., Fig. 4 in Vreeswijk et al. 2004) of high column density of gas around many GRBs, the early high energy radiation from them and their afterglows can destroy the dust in their environment within a radius up to a few tens of parsecs (Waxman & Draine 2000; Fruchter, Krolik & Rhoads 2001; Perna, Lazzati & Fiore 2003). This would pave the way for the afterglow light, but dust in the host galaxy at larger distances could still lead to failure in detecting the OA. In the *high-redshift scenario*, as some fraction of bursts will be located beyond $z \gtrsim 5$ (e.g., Totani 1997; Wijers et al. 1998; Lamb & Reichart 2000), the UV light, which is strongly extinguished by absorption in the Lyα forest, is redshifted into the optical band. Finally, optical faintness can arise if the OA is for some reason intrinsically dark as may happen, e.g., if a relativistic ejecta is decelerated in a *low-density ambient medium* (e.g., Sari, Piran & Narayan 1998; Taylor et al. 2000).

The fraction of dark bursts places important constraints on the fraction of obscured star formation in the Universe (Djorgovski et al. 2001; Ramirez-Ruiz, Trentham & Blain 2002) and the structure of star-forming regions (Lamb 2001; Reichart & Price 2002). Statistical samples studied up to now are unfortunately quite heterogeneous due to large differences in localisation accuracies, localisation time since the onset of the burst, and search strategies. Moreover, effects of observing conditions (e.g., lunar phase) have generally not been taken into account. In many cases, GRBs have been considered dark if no OA was detected, irrespective of how inefficient the search was. In fact, there is no generally accepted criterion for when a GRB is considered dark. In the Swift era it will be essential to have a quick diagnostic tool to flag dark bursts for immediate and/or detailed follow-up (including the near-IR bands) to ensure homogeneity of samples. In this Letter we present a GRB diagram of the optical flux ($F_{\rm opt}$) vs. the optical-to-X-ray spectral index ($\beta_{\rm OX}$) and propose that those bursts which are both optically faint ($R > 23$ after 11 h) and optically subluminous with respect to the fireball model ($\beta_{\rm OX} < 0.5$) should be defined as dark bursts.

2. CURRENT STATUS

A popular working definition of dark bursts is to set a brightness limit at a given time after the GRB, e.g., $R > 23$ at 1–2 days (Djorgovski et al. 2001). Such definitions are necessarily somewhat arbitrary but catch the notion of darkness very well in that the magnitude limits and times correspond to typical search efforts and reaction times. Another approach has been to invoke a physical definition, specifically to require a dark burst to be a significantly obscured burst. It has been argued that GRB 970828 (Djorgovski et al. 2001) and GRB 000210 (Piro et al. 2002) were most likely dark because of optical obscuration.

Fynbo et al. (2001b) demonstrated that the majority ($\gtrsim$75%) of GRBs for which searches for optical afterglow had been unsuccessful were consistent with no detection if they were similar to dim bursts like GRB 000630 in the optical band (see their Fig. 3). Hjorth et al. (2002) found that the dim GRB 980613 had similar properties, i.e., it would have been classified as a dark burst had it not been for the relatively deep search efforts. The afterglow was neither strongly reddened nor at high redshift.

Berger et al. (2002) reached a similar conclusion for the dim GRB 020124 and ascribed the faintness to rapid decay whereas Hjorth et al. (2003) demonstrated that the faintness was largely due to the fairly large redshift of $z = 3.2$ (although not sufficiently large for the burst to

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be dark due to Lyα absorption). Several studies of the rapidly localised HETE-2 burst GRB 021211 arrived at a similar result: it would have been classified as a dark burst due to its rapid fading, but was found to be very bright after ten minutes. It was not strongly reddened and at a moderate redshift (Fox et al. 2003; Li et al. 2003; Crew et al. 2003; Pandey et al. 2003).

In a study of all BeppoSAX bursts with Narrow Field Instruments follow-up, De Pasquale et al. (2003, hereafter D03) found that most optically faint bursts are also X-ray faint. Some bursts, however, appear even fainter in the optical than expected from X-rays. In a comprehensive study, Rol (2004) concluded that most GRBs can be fitted with standard fireball models. Only three were inconsistent with all models, i.e., fainter than the faintest optical expectation from X-rays. These were classified as dark bursts. In addition, Pedersen et al. (2004) have proposed that GRB 001025A, along with some other bursts, appear optically dark because their (X-ray) afterglow is faint and their synchrotron cooling break, ν_c, is located close to the X-ray band.

Recently, more homogeneous samples have been constructed based on BeppoSAX and HETE-2. Stratta et al. (2004) find a dark burst fraction of 4/13 for a sample of bright BeppoSAX bursts. The better search conditions offered by HETE-2, in particular since the Soft X-ray Camera started to deliver accurate and fast localisations, have resulted in this fraction decreasing further to of the order of 10% (Lamb et al. 2004) as anticipated by Fynbo et al. (2001b).

3. THE OPTICAL FLUX VS. $\beta_{\rm OX}$ DIAGRAM

Previous working definitions have been motivated by what makes a burst dark: its faintness. Optical faintness is of course a necessary ingredient in the definition of a dark burst. However, in view of the results that a faint burst does not by itself belong to a separate class (notably GRBs 980613, 000630, 020124, and 021211) and the study of D03 that some bursts may be optically faint simply because they are intrinsically faint, it is clear that optical faintness must be supplemented by another parameter. D03 used the ratio of optical to X-ray flux. Here we will use the optical-to-X-ray spectral index which is more directly related to physical properties of afterglows.

In the simplest fireball models, which have been successfully used to interpret the observed properties of GRB afterglows, the spectral index, β ($F_\nu \propto \nu^{-\beta}$), is governed by the energy distribution of electrons, p, and the location of ν_c (e.g., Sari, Piran & Narayan 1998):

$$\beta = \begin{cases} (p-1)/2 & \nu < \nu_c \\ p/2 & \nu > \nu_c \end{cases} .$$

This result is independent of whether the outflow is collimated or not, or whether the expansion takes place in a constant density or stellar wind environment. In GRB afterglows, the cooling break is frequently found to be located between the optical ($\sim 10^{14}$ Hz) and X-ray ($\sim 10^{18}$ Hz) regimes giving rise to a break in the spectral distribution somewhere between these two frequencies. In some cases, though, it is either positioned below the optical or above the X-rays.

The value of p is usually found to be larger than 2 ($p < 2$ is not ruled out but requires a high-energy cutoff in the electron energy distribution, see e.g., Dai & Cheng 2001) and smaller than 2.5. In a study of 36 BeppoSAX X-ray afterglows, Piro (2004) inferred an average value of $p = 2.26$. In this simple picture, the average $\beta_{\rm OX}$ (where the subscript 'O' stands for 'optical' and 'X' for 'X-ray') is expected to lie between 0.5 ($p = 2$, $\nu_c > 10^{18}$ Hz) and 1.25 ($p = 2.5$, $\nu_c < 10^{14}$ Hz).

In a plot of the optical flux as a function of $\beta_{\rm OX}$, faint bursts will be located in the bottom part. Optically subluminous bursts, i.e., bursts fainter than expected from the fireball model, will be situated in the low $\beta_{\rm OX}$ section. Dark bursts may be defined as bursts that are *both* faint and subluminous. In Fig. 1 we plot the $F_{\rm opt}$–$\beta_{\rm OX}$ diagram for all known GRBs which have an X-ray detection and an optical detection or upper limit (as of August 2004). All data have been interpolated/extrapolated to 11 h (following D03), and are listed in Table 1. For the upper limits we have assumed a decay index of $\alpha = 1$ ($F_\nu \propto t^{-\alpha}$) in the extrapolation. We note that the significance level of reported upper limits vary between bursts, ranging between 2σ and 5σ.

All the R-band magnitudes in Table 1 have been corrected for foreground (Galactic) extinction using the reddening maps of Schlegel, Finkbeiner & Davis (1998). At 11 h, the optical afterglow is usually sufficiently bright that the host galaxy contribution is negligible, but whenever possible we have used the host-subtracted magnitudes reported in the literature. To calculate $\beta_{\rm OX}$ we have proceeded in the following way. For the BeppoSAX bursts we have taken the 1.6–10.0 keV X-ray flux at 11 h from D03 and calculated the flux density at 3 keV. The same procedure was carried out for the Rossi X-ray Timing Explorer (RXTE) bursts, except the 2–10 keV X-ray flux was obtained from various sources in the literature. For the XMM-Newton and Chandra (CXO) data the flux density at 3 keV was derived from the best-fit single power-law with Galactic absorption to the 2–10 keV data. This energy (3 keV) was chosen as it is relatively insensitive to absorption and requires very little extrapolation of the data since it is close to the center of the bandpass with respect to total counts, thus yielding a reliable flux density. Data from XMM-Newton were reduced in a standard way using the XMM-Newton Science Analysis System (SAS, version 6.0.0) and the latest calibration files. The CXO data were reduced in a standard way using the Chandra Interactive Analysis of Observations (CIAO, version 3.0.2) and the latest calibration files (CALDB, version 2.27).

4. DISCUSSION

The bursts classified as dark according to our criterion fulfill $R > 23$ at 11 h and $\beta_{\rm OX} < 0.5$, and are printed in boldface in Table 1. The brightness limit and the time of the observation are necessarily somewhat arbitrarily defined. In the Swift era the data will be obtained within the first hour. To the extent that the simple external shock fireball model can be applied, this should only translate into a shift in the R-band limit.[5] For example, for an average decay index of $\alpha \sim 1$ our adopted limit would be $R \gtrsim 20.5$ at 1 h or $R \gtrsim 18.5$ at 10 minutes.

Dark bursts, i.e., bursts located in the lower left quadrant in the $F_{\rm opt}$–$\beta_{\rm OX}$ diagram, are guaranteed to be spe-

[5] Assuming an unchanged OA spectrum, and that the effect of the reverse shock does not dominate the optical flux; Piran (1999).

TABLE 1
GAMMA-RAY BURSTS THAT HAVE AN UNAMBIGUOUS DETECTED X-RAY AFTERGLOW AND AN OPTICAL FOLLOW-UP.

GRB	Obs.	β_{OX}	$R(11\,h)$	Ref.	GRB	Obs.	β_{OX}	$R(11\,h)$	Ref.	GRB	Obs.	β_{OX}	$R(11\,h)$	Ref.
970111	SAX	< 0.83	>22.2		990907	SAX	< 0.69	>20.9		020127	CXO	< 1.24	>20.4	(22)
970228	SAX	0.81	19.3	(1)	991014	SAX	< 0.63	>22.4		020322	XMM	0.51	23.3	(23)
970402	SAX	< 0.80	>21.5		991106	SAX	< 0.99	>20.2		020405	CXO	0.75	18.3	(24)
970508	SAX	0.69	21.1	(2)	991216	CXO	0.96	16.9	(10)	020427*	CXO	< 0.87	>19.8	(25)
970828	RXTE	< 0.05	>25.0		000115	RXTE	< 1.06	>15.8	(11)	020813	CXO	0.65	19.1	(26)
971214	SAX	0.64	21.9	(3)	000210	SAX	< 0.54	>23.1	(12)	021004	CXO	0.93	18.4	(27)
971227	SAX	< 0.92	>20.3		000214*	SAX	< 0.92	>19.5	(13)	030226	CXO	0.81	19.5	(28)
980329	SAX	0.54	22.6	(4)	000528	SAX	< 0.69	>22.5		030227	XMM	0.62	21.7	(29)
980519	SAX	1.06	18.8	(5)	000529	SAX	< 1.09	>18.8		030328	CXO	0.80	20.2	(30)
980613	SAX	0.69	22.6	(6)	000615	SAX	< 0.78	>22.4		030329	RXTE	0.86	14.7	(31)
980703	SAX	0.71	20.1	(7)	000926	SAX	0.87	18.0	(14)	030528*	CXO	0.63	21.1	(32)
981226	SAX	< 0.51	>23.1		**001025A**	XMM	< 0.43	>24.3	(15)	030723	CXO	1.07	20.9	(33)
990123	SAX	0.65	19.4	(8)	**001109***	SAX	< 0.30	>23.2	(16)	031203*	XMM	0.80	21.0	(34)
990506	RXTE	< 0.06	>23.2		010214	SAX	< 0.63	>22.7	(17)	040106	XMM	0.59	21.8	(35)
990510	SAX	0.86	18.1	(9)	010220	XMM	< 0.94	>21.4	(18)	040223*	XMM	< 0.78	>21.4	(36)
990627	SAX	< 1.02	>20.1		010222	SAX	0.64	19.2	(19)	040701	CXO	< 1.17	>18.1	(37)
990704	SAX	< 0.43	>23.4		011030	CXO	< 0.59	>21.7	(20)					
990806	SAX	< 0.51	>23.3		011211	XMM	0.98	20.1	(21)					

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NOTE. — A burst is marked with an asterisk if the follow-up was not carried out in the R-band, or a deeper limit was available in another band. In these cases, we assumed a spectral index of 0.6 to transform to the R-band. If a burst fulfills our dark burst criteria, i.e., is located in the lower left quadrant of Fig. 1, its name is written in boldface. A total of five bursts are classified as dark according to our proposed scheme. The references refer to the optical follow-up; if void they are extrapolated from the R-band magnitudes listed in Fynbo et al. (2001b). The magnitudes have been corrected for Galactic extinction.

cial in the sense that, with respect to the fireball model predictions, they either have a diminished optical flux or an excessive X-ray flux. The former could be due to high redshift or obscuration, while the latter could be caused by X-ray emission lines (e.g., Reeves et al. 2002) or thermal emission. An X-ray faint burst with a low value of $p < 2$ will also be classified as dark in this scheme. It is important to note that, using this definition of dark bursts, there is no assurance that we will catch *all* obscured or high-z bursts, e.g., if for a particular burst $p = 2.5$ and $\nu_c < 10^{14}$ Hz. Moreover, to answer the question why a specific burst is dark it must be modeled in detail; the F_{opt}–β_{OX} diagram is only a quick diagnostic tool.

We may define gray bursts (see also Rol 2004) as those which have $0.50 \lesssim \beta_{OX} \lesssim 0.55$. In our sample we identify five such bursts, namely GRBs 980329, 981226, 990806, 000210, and 020322. The strict upper limit of $\beta_{OX} \approx 1.07$ in Fig. 1, set by GRBs 980519 and 030723, indicates an upper limit of $p \approx 2.15$. If the value of p is universal (e.g., Waxman 1997), this result would imply that the limit for subluminous bursts is $\beta_{OX} \approx 0.58$. This would shift four of the aforementioned gray bursts into the dark burst category.

There is a clear indication of a correlation between β_{OX} and F_{opt} in Fig. 1. To determine the significance of the correlation we have calculated Spearman's rank coefficient for bursts with detected optical afterglows (filled symbols in Fig. 1) and published redshifts; it is significant at the 3σ level. The apparent correlation is most likely due to several factors, e.g., (i) extinction in host, (ii) high-z, and/or (iii) location of ν_c. We demonstrate the effect of (i) on β_{OX} by gradually increasing the host extinction in a typical burst, GRB 021004, as indicated by the dashed line in Fig. 1. The slope of the line is independent on which burst is selected. In (ii) a burst will follow a similar trend as in (i), albeit in a more discontinues manner, as the optical light is extinguished by Lyman-blanketing. The influence of (iii) on a burst in Fig. 1 is the following: Depending on the location of ν_c, and independently of p, the difference in optical brightness for a given X-ray brightness can be up to 4 magnitudes. More precisely, as ν_c increases, F_{opt} decreases, which also makes β_{OX} decrease.

There are several sources of scatter in the F_{opt}–β_{OX} diagram, e.g., changing z for a given burst will cause it to move (mainly) vertically in the diagram. The standard deviation around a linear fit to the data for bursts with detected afterglows and published redshifts is 3 magnitudes. The standard deviation of the redshifts is 0.8 with a mean of 1.4. Using the equation in Hjorth et al. (2003) (with $z_1 = 1.0$, $z_2 = 1.8$, $\alpha = 1$, and $\beta = 0.6$) we calculate an expected spread of 1.5 magnitudes from redshift alone. The difference in redshifts is hence not able to fully account for the scatter in the diagram. Other sources of scatter are different densities of the ambient medium, diverse viewing angles and probably the jet structure.

The imminent launch of the multi-wavelength observatory Swift, expected to detect ~100 GRBs/year, offers a unique chance to construct a homogeneous sample with

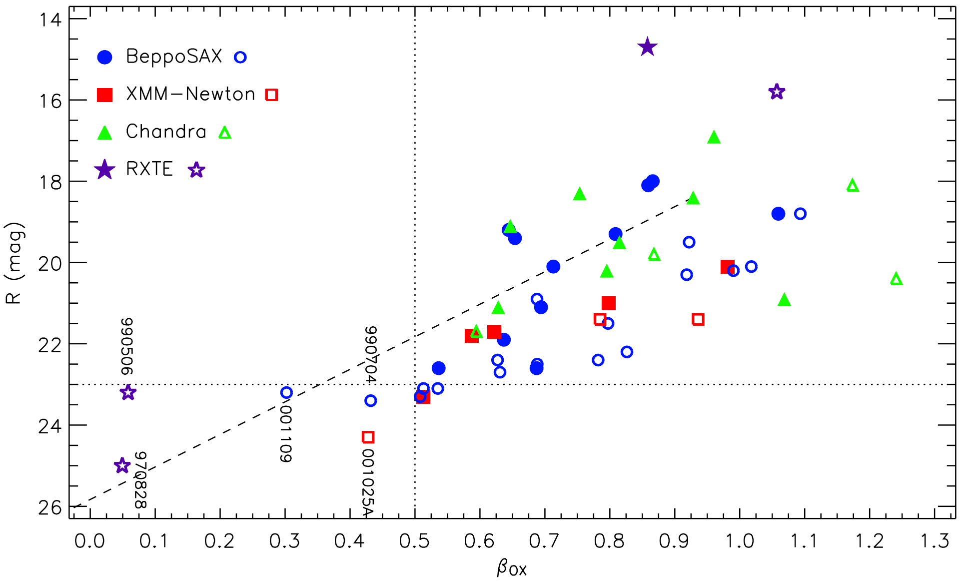

FIG. 1.— A diagram of the optical flux vs. the optical-to-X-ray spectral index ($\beta_{\rm OX}$) for all bursts in Table 1. The R-band magnitudes and X-ray fluxes have been extrapolated to 11 h. The magnitudes have been corrected for Galactic extinction. Filled symbols indicate optical detections while open symbols are upper limits (for both the optical flux and $\beta_{\rm OX}$). We define faint bursts as those which have $R > 23$, and subluminous bursts as those which have $\beta_{\rm OX} < 0.5$. Faint and subluminous bursts are defined as dark bursts and occupy the lower left quadrant of the diagram. The dashed line shows the effect of adding host extinction to GRB 021004.

well-understood selection criteria. Swift will reach an X-ray limit of ∼8 mCrab at 60 s and an optical limit of $R \sim 22$ at ∼300 s (Gehrels et al. 2004). For a Swift burst with an X-ray afterglow detected above this flux limit and no detection in the UVOT image, the value of $\beta_{\rm OX}$ will be below 0.1. This implies that the early (few minutes after the burst) Swift data will be adequate to get a rough location of the burst in Fig. 1 and hence to initiate dedicated follow-up observations.

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