The Astrophysical Journal, 699:1087–1091, 2009 July 10 doi:10.1088/0004-637X/699/2/1087

OPTICAL CLASSIFICATION OF GAMMA-RAY BURSTS IN THE *SWIFT* ERA

A. J. van der Horst[1], C. Kouveliotou[2], N. Gehrels[3], E. Rol[4], R. A. M. J. Wijers[5], J. K. Cannizzo[3,6], J. Racusin[7], and D. N. Burrows[7]
[1] NASA Postdoctoral Program Fellow, NSSTC, 320 Sparkman Drive, Huntsville, AL 35805, USA; Alexander.J.VanDerHorst@nasa.gov
[2] NASA Marshall Space Flight Center, NSSTC, 320 Sparkman Drive, Huntsville, AL 38505, USA
[3] NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[4] Department of Physics & Astronomy, University of Leicester, University Road, Leicester, LE1 7RH, UK
[5] Astronomical Institute, University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands
[6] CRESST/Joint Center for Astrophysics, University of Maryland, Baltimore County, Baltimore, MD, 21250, USA
[7] Department of Astronomy & Astrophysics, Pennsylvania State University, State College, PA 16802, USA
Received 2009 February 4; accepted 2009 April 29; published 2009 June 18

ABSTRACT

We propose a new method for the classification of optically dark gamma-ray bursts (GRBs), based on the X-ray and optical-to-X-ray spectral indices of GRB afterglows, and utilizing the spectral capabilities of *Swift*. This method depends less on model assumptions than previous methods, and can be used as a quick diagnostic tool to identify optically sub-luminous bursts. With this method we can also find GRBs that are extremely bright at optical wavelengths. We show that the previously suggested correlation between the optical darkness and the X-ray/gamma-ray brightness is merely an observational selection effect.

Key words: gamma rays: bursts

1. INTRODUCTION

The discovery of gamma-ray burst (GRB) afterglows at optical wavelengths (van Paradijs et al. 1997) led to the confirmation of the extragalactic nature of the phenomenon (Metzger et al. 1997). In the last decade, a multitude of photometric and spectroscopic observations have established the relativistic blast wave model for the afterglow emission (Rees & Meszaros 1992; Wijers et al. 1997). Coordinated multi-wavelength observations have revealed the nature of a large fraction of GRB progenitors (Galama et al. 1998; Hjorth et al. 2003; Stanek et al. 2003) and allowed studies of their host galaxies (Sahu et al. 1997). In very few cases, however, GRB counterpart searches were not successful in identifying a fading transient at the GRB explosion site. Only a few months after the first afterglow detection, Groot et al. (1998) found the first optically dark event, GRB 970828. They used the concept of "dark burst" to indicate that the event was detected in X-rays but not in the optical, down to deep limiting magnitudes at a few hours after the burst. Since then, observers classified many bursts as dark, although in a substantial fraction of these the absence of an optical counterpart could simply be due to a lack of observational sensitivity or a large delay between the GRB trigger time and the start of the follow-up observations. Even excluding these cases, there remain a few events that do not fall within these observational constraints. Several explanations have been proposed in the literature for their dark nature: they could be intrinsically faint at optical wavelengths compared to the X-rays, or they might reside at high redshifts, or they might be obscured by gas and dust in their host galaxies (e.g., Rol et al. 2005).

To get a better handle on the optical darkness of GRB afterglows by eliminating some of the observational effects, two major efforts were undertaken before the launch of NASA's *Swift* GRB satellite. Both constructed a consistent method to define what classifies a GRB as being dark. Jakobsson et al. (2004) defined dark bursts solely based on their optical-to-X-ray emission spectral index being lower than a certain theoretical value of 0.5. Rol et al. (2005) applied a more elaborate approach, extrapolating the observed X-ray flux to the optical regime by using their X-ray spectral and temporal indices and assuming that the GRB explosion followed the relativistic blast wave model. Both approaches were demonstrated on samples of pre-*Swift* GRBs and resulted in largely overlapping dark GRB sets.

In this paper, we examine the identification of dark bursts in the light of the new observational window in the X-rays and the optical wavelengths opened by the *Swift* satellite, seconds after the detection of the GRB prompt emission. We have studied the sample of long *Swift* GRBs from Gehrels et al. (2008) with X-ray and optical detections or stringent upper limits (Tables 2 and 3 from Gehrels et al. 2008; optical fluxes from ground-based telescopes and Swift's UV Optical Telescope; X-ray spectral indices from Racusin et al. 2009). We added to the sample two *Swift* GRBs: GRB 050401 (De Pasquale et al. 2006; Watson et al. 2006) and GRB 050410 (Mineo et al. 2007), with an optical detection and an optical upper limit, respectively. We also added two *HETE-II* GRBs: GRB 051022 (Nakagawa et al. 2006; Rol et al. 2007; Castro-Tirado et al. 2007) and GRB 051028 (Castro-Tirado et al. 2006; Urata et al. 2007), with an optical upper limit and an optical detection, respectively. To conform with the Gehrels et al. (2008) data set we inter- or extrapolated the X-ray and optical fluxes of these last four GRBs to 11 hr and corrected for galactic extinction.

In Section 2, we apply and discuss the current dark burst classification schemes to this entire sample. We propose a new method in Section 3, which utilizes the unique capabilities of *Swift*. In Section 4, we briefly discuss the GRBs that are classified as optically dark by our method. Section 5 examines the apparent correlation between optical darkness and X-ray/gamma-ray brightness, and we summarize our results in Section 6.

2. CURRENT DARK BURST CLASSIFICATION METHODS

The *Swift* GRB afterglow data are unprecedented in that they start typically within 2 minutes after each GRB trigger and monitor temporal evolution with high resolution and for long periods (from days to tens of days). Several afterglow studies have now established that GRB X-ray light curves are much more complex than previously thought: the canonical *Swift* X-ray light curve displays additional (earlier) phases of steep and slow decay on what was earlier considered the "normal" decay (Nousek et al. 2006; Zhang et al. 2006). Various explanations have been put forward for this behavior (e.g., Granot et al. 2006; Panaitescu et al. 2006); at the same time it is becoming obvious that simply extrapolating the X-ray flux to the optical bands using *temporal* decay indices and predictions from the standard blast wave model is not straightforward and should be done with great caution. Extrapolating the X-ray flux to the optical bands by adopting their X-ray *spectral* index, however, is more sensible since it only assumes that the broadband spectral energy distribution is caused by synchrotron radiation, which is well established for GRB afterglows. We note here that Inverse Compton radiation might also have a small effect in the X-ray spectrum, as it could make the burst optically sub-luminous compared to the X-ray emission.

According to the above, both dark-GRB determination methods, by Jakobsson et al. (2004) and Rol et al. (2005), have their drawbacks, and we believe that an improvement can now be made with the new results that *Swift* has provided. The method of Rol et al. (2005) is most affected, as it uses both spectral and temporal indices, while the Jakobsson et al. (2004) method requires no temporal evolution assumptions. In the latter method, the optical and X-ray fluxes are interpolated or extrapolated to 11 hr after the burst and plotted together with a line of constant optical-to-X-ray spectral index $\beta_{\rm OX}$; bursts that fall below that line are classified as dark. The drawback of this method, which has also been pointed out in Jakobsson et al. (2004), is the choice of the dividing $\beta_{\rm OX}$; they chose a value of 0.5 as a minimum based on the following arguments. In synchrotron radiation, the photon spectral index in the optical and X-rays depends on the power-law index p of the electron energy distribution as either $(p-1)/2$ or $p/2$, if the cooling frequency is situated above or below the observing band, respectively. In the simplest form of the blast wave model (e.g., Wijers et al. 1997; Sari et al. 1998), p is expected to be larger than 2 leading to $\beta_{\rm OX} \geqslant 0.5$. In most cases, p is indeed found to be greater than 2 leading to $\beta_{\rm OX} \geqslant 0.5$, but it has been shown that $p < 2$ is possible, both observationally and theoretically, by introducing a high-energy cutoff in the electron energy distribution (Dai & Cheng 2001; Panaitescu & Kumar 2002; Bhattacharya & Resmi 2004; Starling et al. 2008).

3. OUR CLASSIFICATION METHOD

We propose a new method for dark burst classification which does not involve the temporal index of the X-ray afterglow light curves and has fewer assumptions regarding the emitting electron energy distribution. Our main assumptions are that the underlying emission mechanism in both the optical and X-rays is synchrotron radiation, and that the emission in both frequency bands originates from the same source. In that case, given a certain value for the X-ray spectral index $\beta_{\rm X}$, the optical spectral index $\beta_{\rm O}$ should either have the same value or a value of $\beta_{\rm X}-0.5$, if there is a cooling break in between the optical and X-ray regimes. This implies that $\beta_{\rm OX}$, the spectral index between the X-ray and optical regime, should be in between $\beta_{\rm X}$ and $\beta_{\rm X}-0.5$. In Figure 1, we plot $\beta_{\rm OX}$ versus the X-ray spectral index $\beta_{\rm X}$ for the *Swift* GRB sample from Gehrels et al. (2008; uncertainties in parameters at 90% and upper limits at 3σ confidence level). In this method again, $\beta_{\rm OX}$ is constructed from the interpolated/extrapolated optical and X-ray flux at 11 hr; moreover, $\beta_{\rm X}$ is quickly available with good accuracy from the *Swift* XRT for

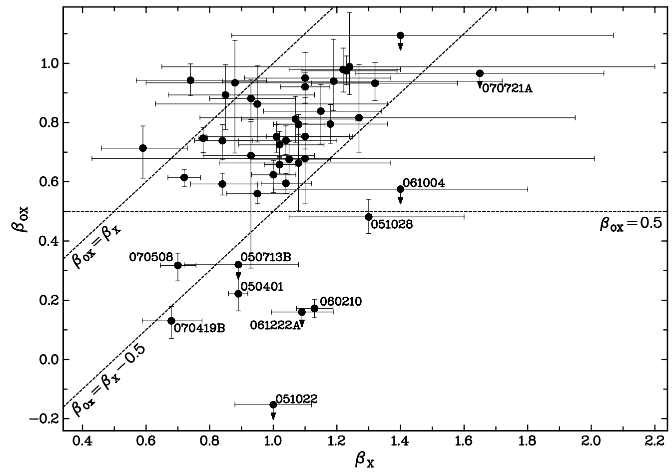

Figure 1. Spectral index $\beta_{\rm OX}$ between the optical and X-ray observing bands vs. the X-ray spectral index $\beta_{\rm X}$ for our sample of *Swift* GRBs (error bars at 90% and upper limits at 3σ level). The optical-to-X-ray spectral index is given at 11 hr after the burst. The horizontal dashed line indicates the dark burst criterion from Jakobsson et al. (2004): the optical-to-X-ray spectral index $\beta_{\rm OX}$ is equal to 0.5. The diagonal dashed lines indicate $\beta_{\rm OX} = \beta_{\rm X}$ and $\beta_{\rm OX} = \beta_{\rm X} - 0.5$.

almost all GRBs. It is necessary to take these spectral indices at late times, i.e., after several hours, since some GRBs have bright optical emission at early times, presumably from reverse shocks.

In principle, all GRBs should be found in a band between the lines of $\beta_{\rm OX} = \beta_{\rm X}$ and $\beta_{\rm OX} = \beta_{\rm X} - 0.5$. There are two regions of interest in Figure 1: GRBs with brighter than expected optical emission at the left upper part of the Figure, and GRBs where $\beta_{\rm OX}$ is even shallower than $\beta_{\rm X} - 0.5$. We define these latter bursts to be optically sub-luminous, or dark, in our classification method. The bursts for which the error bars on $\beta_{\rm X}$ overlap with the line $\beta_{\rm OX} = \beta_{\rm X} - 0.5$ are not classified as dark in our method. The resulting dark burst population in our sample is different than that obtained applying the criterion of Jakobsson et al. (2004), which in Figure 1 are those GRBs which are below the horizontal line $\beta_{\rm OX} = 0.5$. Also, we note that in our sample there are three events where there is clearly a detection in the optical wavelengths, defying their classification of dark as such. We discuss the individual dark bursts as well as the optical bright events in the following section.

Further, one of the main differences between Jakobsson et al. (2004) and our method is that we accommodate here all values that are found for the various spectral indices, and thus all implied values of p. Thus, bursts with a shallow X-ray spectrum (indicating a low value for p), can still be "normal", i.e., not dark, in our method, while they could be classified as being dark in the method of Jakobsson et al. (2004). Indeed, as was already pointed out by Jakobsson et al. (2004), the fact that a certain burst has a low value of p should not have any implications for its "darkness" classification, especially given that various observational studies have shown that there is not a single universal value of p but a wide distribution of values (e.g., Panaitescu & Kumar 2002; Starling et al. 2008). Conversely, if a GRB has a steep X-ray spectrum, the value for $\beta_{\rm OX}$ should also be high, and if this is not the case it could be classified as a dark burst. The latter is not accommodated in the Jakobsson et al. (2004) method; it is correctly predicted in the method by Rol et al. (2005), although there again the temporal indices are the unreliable factor in the classification.

4. COMMENTS ON INDIVIDUAL BURSTS

Figure 1 shows that there are several GRBs outside of the band between the lines of $\beta_{OX} = \beta_X$ and $\beta_{OX} = \beta_X - 0.5$, which we will discuss here in some detail.

4.1. Optically Dark Bursts

Looking at Figure 1, we notice that there are some GRBs which are clearly classified as dark by the method of Jakobsson et al. (2004) and by our method, but there are also some differences. GRBs 051022, 061222A, 050401, and 060210 are classified as dark by both methods; the first two are optical upper limits, and the latter two are actually detections but optically sub-luminous events. GRBs 050713B, 070508, and 070419B are classified as dark by Jakobsson et al. (2004) since they have $\beta_{OX} < 0.5$, but not according to our method; given the low value for β_X, these are cases of $p < 2$. GRB 051028 is identified as dark by our method, although the uncertainty in β_X is rather large, and is not identified as such by the Jakobsson et al. (2004) method. Finally, GRBs 061004 and 070721A have optical upper limits and are not classified as dark by the Jakobsson et al. (2004) method, and due to their large uncertainties in β_X also not by our method. We note that the latter two are situated in the region of the diagram of possible dark bursts with a high value of p; given their large errors in the determination of β_X, we will not discuss these particular two events further.

Detailed analyses of GRB 050401 (De Pasquale et al. 2006; Watson et al. 2006) and GRB 060210 (Curran et al. 2007) show that the sub-luminous optical flux of these events can be explained by a combination of moderate local (host galaxy) extinction and high redshift (2.90 and 3.91, respectively). GRB 051022 was detected at X-ray, millimeter and radio frequencies, and optical observations showed a moderately bright host galaxy but no optical afterglow emission down to deep limits (Rol et al. 2007; Castro-Tirado et al. 2007). Broadband modeling of the afterglow by Rol et al. (2007) constrained not only the physical parameters of the blast wave, but also the severe host galaxy extinction of this relatively nearby ($z = 0.809$) GRB. The afterglows of GRBs 051028 and 070419B were detected in the optical, but there are no spectroscopic redshifts available; and also not for GRB 050713B and 061222A, which are not detected in the optical. There are not enough data available to investigate these events further, although we note that for GRB 051028 a relatively high redshift is the most probable cause for it being (marginally) optically sub-luminous (Castro-Tirado et al. 2006).

4.2. Optically Bright Bursts

The upper left part of Figure 1, above the $\beta_{OX} = \beta_X$ line, is of interest, because it reveals GRBs that are optically super-luminous. In our sample two events have β_{OX} values above the $\beta_{OX} = \beta_X$ line, GRB 060607A and GRB 060526, but they are consistent with β_X at the 90% confidence level. Two more are marginally above, but consistent with, that line, namely GRB 050908 and GRB 050801. All these four events are at the low end of the β_X distribution in our sample, with GRB 060607A actually having the lowest β_X value of the whole sample.

These optically bright sources are consistent with $\beta_{OX} = \beta_X$ within measurement uncertainties. However, three of these sources are at a high redshift ($z = 3.08$, 3.22, and 3.34), and a moderate host-galaxy extinction would increase the value of β_{OX} in Figure 1 while β_X remains at the same value, i.e., the source would move up vertically in this Figure away from the $\beta_{OX} = \beta_X$ line. This would make the brighter than expected optical brightness of these sources more significant. We note that a change in β_{OX} due to a host galaxy extinction of A_V magnitudes can be approximated by 0.13 A_V. For an average extinction of ~ 0.2 magnitudes in the source frame, as found for a pre-*Swift* sample of GRB host galaxies (Kann et al. 2006), this effect is negligible. However, some studies (e.g., Cenko et al. 2009) show that several individual host galaxies display strong extinction with $A_V \sim 1$ or larger, which does have a significant effect on the value of β_{OX}.

With regard to the spectral indices of GRBs in that part of Figure 1, there are various possibilities for their deviating values. Inverse Compton radiation could play a role at X-ray frequencies, which would flatten the X-ray spectral index but also increase the X-ray flux and thus decrease β_{OX}. It is not obvious that correcting for this effect would move these sources into the allowed band of spectral indices in Figure 1. A second possible explanation for the extreme optical brightness could be that the spectrum is not described by one broadband spectrum, but that there is an extra emission component at optical wavelengths. This could be caused by a double-jet configuration or refreshed shocks, which have both been invoked for explaining some well sampled GRB afterglows (e.g., Berger et al. 2003; Starling et al. 2005).

5. OPTICAL DARKNESS VERSUS X-RAY AND GAMMA-RAY BRIGHTNESS

We compare below the X-ray and gamma-ray brightness of the GRBs classified as optically sub-luminous with our method, to our whole sample. Figure 2 shows the distributions of their X-ray flux F_X, and gamma-ray fluence S_γ in the 15–150 keV range. The gamma-ray fluences of the two *HETE-II* bursts, GRB 051022 and GRB 051028, have been converted to values in the correct energy range by using the fluences and spectral parameters provided in Nakagawa et al. (2006) and Golenetskii et al. (2005), respectively. Figure 2 strongly suggests that optically dark GRBs are bright in X-rays and relatively bright in gamma rays, as also suggested earlier by De Pasquale et al. (2003) and Rol et al. (2005). We have explored the possibility of an observational selection effect to explain this latter correlation: if there is a positive correlation between optical and X-ray/gamma-ray brightness, it is easier to identify optically dark bursts if they are bright in X-rays and gamma rays. Here we show that this selection effect is indeed in play.

Figure 3 exhibits β_{OX} versus X-ray flux; the dashed lines indicate optical magnitudes of 23.5 and 25, which is roughly the limiting magnitude range of the current deepest searches for optical afterglows. We see here the same trend as that seen in the top histogram of Figure 2, namely the correlation between optical darkness and X-ray brightness. Figure 3 shows that there are no bursts below the magnitude 25 line, and only one between 23.5 and 25 (GRB 051022). Above magnitude 23.5 the GRBs are quite homogeneously distributed, clearly suggesting an observational selection effect. This only explains the selection effect for the correlation between the optical darkness and X-ray brightness. The correlation between the optical darkness and gamma-ray fluence can be understood from a different correlation, studied for this sample by Gehrels et al. (2008), namely the positive correlation between the X-ray flux and gamma-ray fluence.

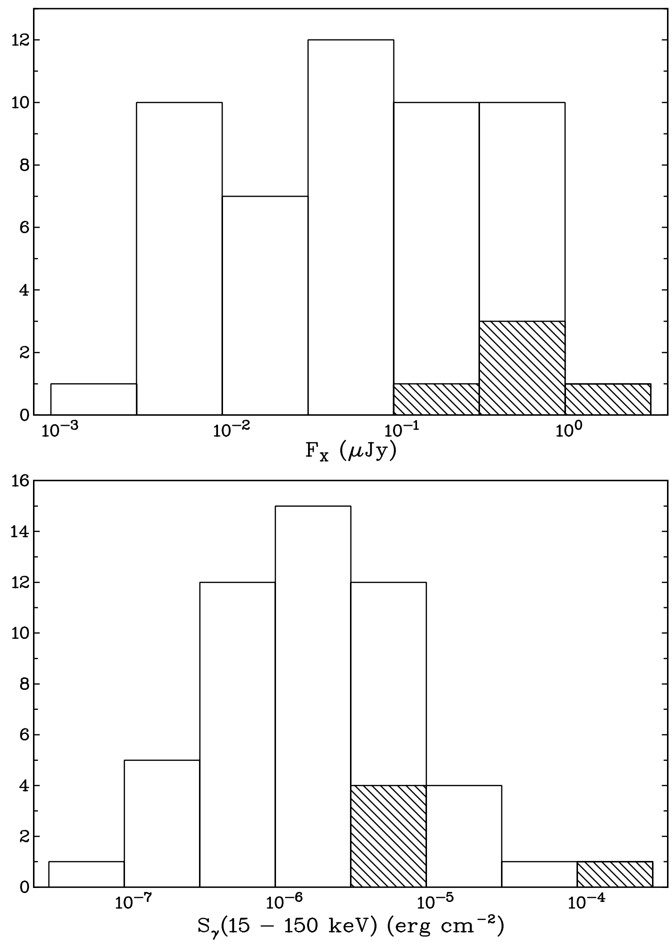

Figure 2. Histogram of the X-ray flux F_X (top) and the gamma-ray fluence S_γ in the 15–150 keV energy range (bottom) for our total sample of *Swift* GRBs. The GRBs classified as dark bursts by our method are indicated by double hatched histograms. These histograms suggest that almost all optically dark GRBs are bright in X-rays and relatively bright in gamma rays.

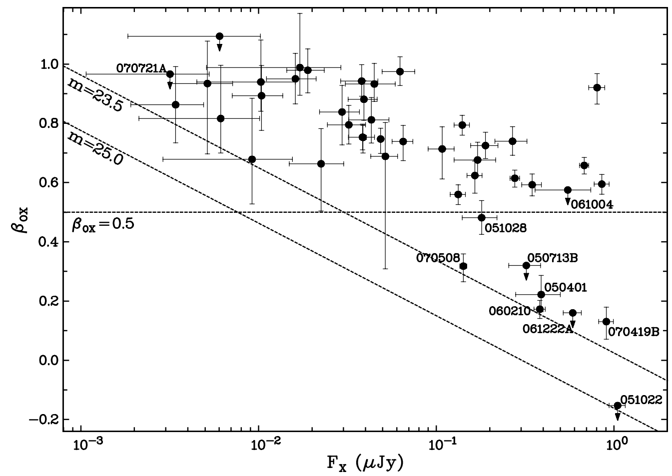

Figure 3. Spectral index β_{OX} between the optical and X-ray observing bands vs. the X-ray flux F_X for our sample of *Swift* GRBs (error bars at 90% and upper limits at 3σ level). Both the spectral index and the X-ray flux are given at 11 hr after the burst. The horizontal dashed line indicates the dark burst criterion from Jakobsson et al. (2004): the optical-to-X-ray spectral index β_{OX} is equal to 0.5. The diagonal dashed lines indicate optical magnitudes of 23.5 and 25, showing that optically dark GRBs being bright in X-rays is merely an observational selection effect.

6. CONCLUSIONS

We have proposed a new method for the classification of optically dark gamma-ray bursts (GRBs), based on the X-ray and optical-to-X-ray spectral indices of GRB afterglows, and utilizing the spectral capabilities of *Swift*. When plotting the optical-to-X-ray spectral index β_{OX} versus the X-ray spectral index β_X, all the GRBs below the dividing line of $\beta_{OX} = \beta_X - 0.5$ are classified as dark. This method depends less on model assumptions than previous methods, and can be used as a quick diagnostic tool to identify dark bursts. In particular, the method assumes only a synchrotron spectrum from optical to X-rays originating in one emission region, allows for the large range of observed values for the electron energy distribution index p, and excludes any uncertainties in the temporal evolution of the GRB blast wave. With our classification method we can also find GRBs that are extremely bright in the optical, i.e., in which β_{OX} is too steep compared to β_X. We suggest that this could be due to other radiation processes besides synchrotron radiation at X-ray frequencies, e.g., Inverse Compton; or due to extra emission in the optical, for example caused by a double-jet configuration or refreshed shocks.

Utilizing our sample of *Swift*, and two *HETE-II*, GRBs, we have shown that the previously suggested correlation between the optical darkness and the X-ray/gamma-ray brightness is merely an observational selection effect. In order to further the understanding of dark bursts, in particular the effect of host-galaxy extinction on the blast wave emission, it is important to undertake dedicated searches for dark burst candidates from early-time optical, UV, and (near-)infrared observations. Since the afterglow physics in the first minutes to hours after the burst is quite uncertain, these early-time observations should be followed up by observations at roughly half a day after the burst with at least 4 m class telescopes, in order to constrain the optical darkness as stringent as possible. Constraining the full broadband spectrum by including radio and millimeter observations, as for example is done for GRB 051022, could then provide important clues on the nature of dark bursts and their host galaxies.

We thank Pall Jakobsson for useful discussions and suggestions. A.J.vd.H. was supported by an appointment to the NASA Postdoctoral Program at the MSFC, administered by Oak Ridge Associated Universities through a contract with NASA. J.R. and D.N.B. gratefully acknowledge support from NASA contract NAS5-00136.

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