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GROND view of "dark bursts" and the related bias in host galaxy properties

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Abstract. Using the afterglow detection statistics of the systematic follow-up observations performed with GROND since mid-2007, we have derived a 90% (35/39) complete sample wrt. detection rate of optical/NIR afterglows. We find that the faint optical emission in dark bursts is mainly due to these two factors: (i) moderate intrinsic extinction at moderate ($z<5$) redshifts, and (ii) a redshift >5 (22% of the cases). Follow-up observations of the host galaxies of such high-A_V afterglows reveal that these hosts are predominantly redder, more massive and more luminous than the hosts of optically bright afterglows.

Key words. Gamma-ray burst: general – ISM: dust, extinction – Galaxies: star formation

1. Introduction

1.1. Dark GRBs and GROND observation statistics

For more than a decade, a full understanding of the nature of dark gamma-ray bursts (GRB) has eluded scientists: while each long-duration GRB typically has an X-ray afterglow, optical/NIR emission is only seen for 40-60% of them. Various alternative explanations have been proposed for the darkness in the optical (e.g., Fynbo et al. 2001). The afterglow could (i) have an intrinsically low luminosity; (ii) be strongly absorbed by intervening material, either very locally around the GRB or along the line-of-sight through the host galaxy, or (iii) be at high redshift ($z > 6$) so that Lyα blanketing and absorption by the intergalactic medium would prohibit detection in the frequently used *R* band (Lamb & Reichart 2000).

Here, we use the afterglow detection rate of GROND, a dedicated ground-based GRB follow-up instrument, to derive new constraints on the fraction of dark bursts. Full details can be found in Greiner et al. (2011).

GROND, a simultaneous 7-channel optical/near-infrared imager (Greiner et al. 2008) at the 2.2 m MPI/ESO telescope at La Silla (Chile), started operation in May 2007. GROND has been built as a dedicated GRB follow-up instrument and has observed basically every GRB visible from La Silla (weather allowing) since April 2008. It is obvious that the later after a GRB trigger the GROND observation starts, the lower the fraction of afterglow detections is (Tab. 1). This is readily explained by the fading of afterglows and the limiting sensitivity of the instrument/telescope. Surprising, however, is the high detection rate in the first two time bins – this will be discussed in the following.

Selecting all bursts which have been observed with GROND within less than 240 min (4 hrs) after the *Swift* trigger and which have XRT-detected afterglows (until 31 March 2010), we find 35 afterglow detections out of a total of 39 long-duration bursts.

Table 1. GROND afterglow detection fraction of long-duration bursts as a function of time delay of the start of the observation after the GRB trigger. Based on a total of 128 bursts observed between 070802 and (inclusive) 100331A.

Delay (hrs)	detected vs. observed (fraction)	fraction of total
<0.5	20 /22 (91%)	17%
0.5–4	15 /17 (88%)	14%
4–8	10 /21 (48%)	16%
8–16	22 /36 (61%)	28%
16–24	13 /22 (59%)	17%
> 24	5 /10 (50%)	8%

1.2. Fitting broad-band spectral energy distributions

GROND and *Swift*/XRT data have been reduced in the standard manner using pyraf/IRAF (Tody 1993; Küpcü Yoldaş et al. 2008) for the optical/NIR data and the XRT pipeline for the X-ray data. We then combined XRT and Galactic foreground (Schlegel et al. 1998) extinction-corrected GROND data to establish a broad-band spectral energy distribution (SED).

These SEDs have been fit with two alternative models: (i) a single power law with free slope and normalization, plus free source-intrinsic extinction of SMC/LMC or MW-type (for the GROND data) and Galactic plus rest-frame equivalent neutral hydrogen column density (for the X-ray data) assuming solar abundances; or (ii) a broken power law where the break energy is left free but the difference in the two slopes is fixed to 0.5, and all other parameters are left free as above. Except for seven GRBs (080605, 080710, 080913, 081029, 081228, 090926B, 091221) all GRBs are better fit with a break between the X-ray and the optical/NIR. With the exception of five bursts (GRBs 070802, 080210, 080605, 080805, 090102), the SEDs of the afterglows are consistent with being reddened with an SMC extinction law.

1.3. The nature of dark bursts

Depending on which dark burst classification is used, our sample contains 25–40% dark bursts, fully consistent with the hitherto known fraction of dark bursts of 25%–42% (e.g., Fynbo et al. 2009).

The main results of the SED fitting with respect to the "dark" burst issue can be summarized as follows (the following properties are non-exclusive, and we use the definition of van der Horst et al. (2009) rather than Jakobsson et al. (2004)): (1) Four out of the nine dark bursts are faint due to non-zero, but moderate ($A_V \approx 0.2 - 1.5$) extinction: 070802, 080210, 080516, 080805. The measured extinction in many cases appears enhanced to the observer due to a moderate redshift of the burst (see Fig.

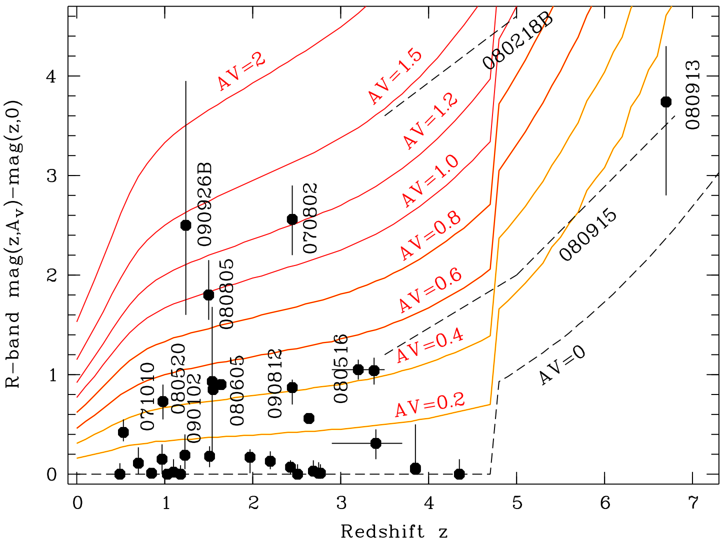

Fig. 1. The effect of the combination of various values of intrinsic extinction A_V (lines with labels) and redshift, producing an effective dimming in the R band as given on the y-axis. The solid lines have been computed assuming a dust extinction curve as described in Reichart (1999) but with no 2175 Å bump and an opacity due to intergalactic hydrogen approximated by $\tau(\mathrm{HI}) = 2.6 \times (1+z)^{3.3}$ for 700 nm/$(1+z) \leq 121.6$ nm (Valageas et al. 1999). Dots represent the GRBs of our sample for which we have an A_V measurement from the GROND SED. GRBs with effective R-band reduction of >0.5 mag are labeled. Moderate A_V at moderate redshifts can easily produce a dimming of 1–3 mag in the R band.

1). (2) One burst (090904B) is behind an additional A_V~2 mag dust on top of the nominal A_V~5 Galactic foreground which could either be due to patchiness of the foreground or due to host galaxy extinction. (3) Two bursts are faint (in r') due to high redshift ($z > 5$), namely GRB 080913 and 090429B. This corresponds to a fraction of 22%±8% of the dark bursts. (4) The remaining two of our "dark" GRBs, 080218B and 080915, are either at large redshift or moderate A_V, or both – so they belong to one of the above two groups (1) or (3). (5) Even bursts with good evidence for a spectral break and $\beta_{OX} = 0.5$ do sometimes require extinction, in particular if the break is near the optical (rather than X-ray) range.

Summarizing, the faint optical afterglow emission of "dark bursts", where we used the definition of van der Horst et al. (2009), is due to two factors, namely moderate ($0.3 < A_V < 1.5$ mag) intrinsic extinction at $z < 5$, or a redshift >5 (about 25% of the dark bursts). We emphasize here that we (1) measure the optical/NIR SED, and (2) make no assumptions on the host properties. Thus, our sample of bursts is the first with properly measured A_V values which neither requires a relative shifting of different filter measurements nor suffers from small wavelength coverage.

2. Host galaxies of highly extinguished afterglows

2.1. Sample selection and observations

The host galaxy sample presented is based on a direct measurement of large visual extinction along the GRB line of sight ($A_V^{GRB} > 1$ mag) from multi-color (NIR to X-ray) afterglow observations. Specifically, eight GRB afterglows (GRBs 070306, 070802, 080605, 080607, 080805, 081109, 090926B and 100621A) fulfill the selection criterion and define our host sample. Our sample is a direct result of afterglow observations. The selection itself is hence not limited by galaxy brightness, nor does it introduce a bias towards luminous galaxies. Afterglow measurements for the initial selection have been obtained from the literature or by analyzing photometric optical/NIR data from the GROND archive.

Optical and near-infrared measurements of the afterglows of GRBs 070306, 070802, 080605, 080607, 080805 and 090926B or results thereof are taken from Jaunsen et al. (2008); Krühler et al. (2008); Perley et al. (2011); Greiner et al. (2011); Zafar et al. (2011), respectively. GROND observations of the afterglows of GRB 081109 and GRB 100621A are described in Krühler et al. (2011); as are the details of this chapter.

Late follow-up observations were initiated first with GROND, and in case of non-detections in individual filters were continued with telescopes of successively increasing aperture size, specifically with EFOSC/SOFI at the NTT (4m class) and FORS2/HAWKI at the VLT (8m class). In one case without published redshift (GRB 081109), the photometric imaging was complemented by a spectroscopic redshift determination with FORS2.

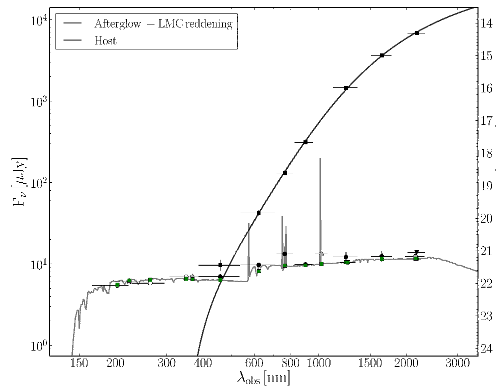

Fig. 2. Comparison of the GROND-only SED of the afterglow of GRB 100621A (steep curve; $A_V = 3.9 \pm 0.2$ mag) with the SED of the host galaxy which is the flattest among all GROND-detected hosts, and is even seen in the UV by Swift/UVOT.

2.2. Host SED fitting

UV/optical/NIR photometry of the hosts of the selected GRBs were analyzed in a standard way using stellar population synthesis (SPS) techniques to convert luminosities into stellar masses M (e.g., Bell et al. 2003; Ilbert et al. 2010) within LePhare[1]. In detail, 3×10^6 galaxy templates based on models from Bruzual & Charlot (2003) with a universal IMF (Chabrier 2003) and different ages, star formation histories, extinction laws, reddening values and metallicities were fit to the data. In addition, emission lines are taken into account by converting the de-reddened UV luminosity into a star formation rate, and hence line strengths of Ly-α, Hα, Hβ, [OII] and [OIII] following Kennicutt (1998) and Ilbert et al. (2009). For a direct comparison with results published in the literature (e.g., Fontana et al. 2006; Marchesini et al. 2009; Ilbert et al. 2010; Savaglio et al. 2009) the attenuation law from Calzetti et al. (2000) derived for starburst galaxies is used, unless different reddening laws provide a better fit to the host data at 90% confidence. We caution that access to the rest-frame NIR, which is the best tracer of the stellar mass of the galaxy, is somewhat limited for part of the sample. However, all hosts are detected in at least one filter redwards of the 4000 Å break, which allows a reasonable estimate of $M_\star$ of a galaxy (e.g., Glazebrook et al. 2004; Ilbert et al. 2009; Savaglio et al. 2009).

The general properties of the selected GRB host galaxies are diverse. They have $(R-K)_{AB}$ colors ranging from flat and blue, $(R-K)_{AB} \sim 0$ mag, to extremely red, $(R-K)_{AB} \sim 3$ mag, and host extinction values between 0–2 mag. The extinction measured for the afterglow emission is not at all correlated to that in the hosts – a good example is GRB 100621A which has one of the highest afterglow A_V values and one of the bluest hosts known to date (Fig. 2). This particular example provides evidence for a patchy dust component where the geometry of the dust distribution and not the properties of the host galaxy makes the single GRB sightline dust-enriched.

[1] http://www.cfht.hawaii.edu/~arnouts/LEPHARE

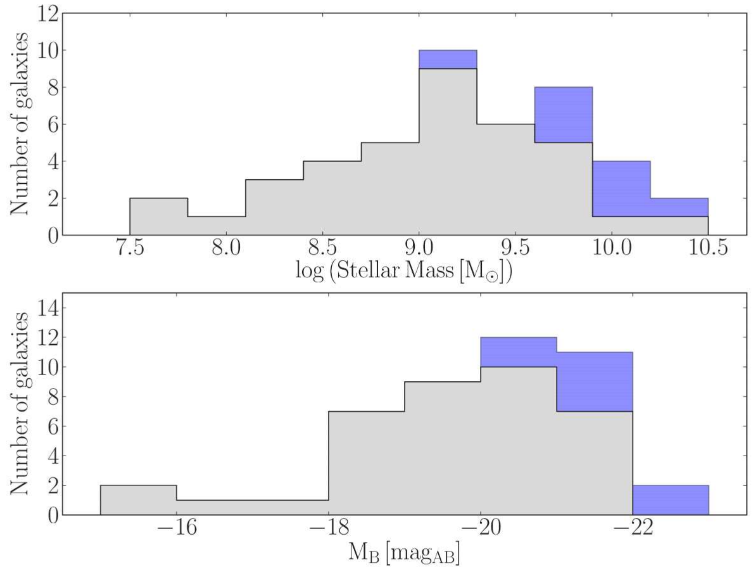

Fig. 3. Distributions of stellar masses and luminosities of the hosts of the highly extinguished afterglows (blue) and the host sample from Savaglio et al. (2009).

The distributions of stellar mass and absolute magnitude of our host sample are also broad, with values between $\log(M[M_\odot]) = 9.0$ to $\log(M[M_\odot]) = 10.4$ and M_B between -20.3 mag and -22.6 mag. These absolute brightnesses are in a range between several tenths to few $L^\star$ as compared to the general field galaxy population at the same redshift. The average SFR and SSFR are about 30 $M_\odot$/yr and $\langle \log(\mathrm{SSFR}\ [\mathrm{yr}^{-1}]) \rangle \sim -8.3$, respectively. The average growth time is 0.2 Gyr, which illustrates that not only optically selected hosts, but also those of highly-reddened afterglows are very efficient in producing stars. A rough estimate on the metallicity of the hosts can be obtained if these GRB hosts follow the fundamental plane as defined from nearby SDSS galaxies (Manucci et al. 2010). With a given stellar mass and SFR, the host galaxies in this sample are expected to have metallicities in a range between $8.2 < 12 + \log(\mathrm{O/H}) < 8.9$. We caution that the SFRs were derived using the rest-frame UV flux, which is sensitive to the assumptions on the dust extinction properties.

Despite the relatively broad range in mass and absolute magnitude, a comparison with the previously known sample of Savaglio et al. (2009) shows that our selected hosts have typically higher luminosities and stellar masses (Fig. 3). A two-sample KS test returns p-values of 0.002 for the stellar mass, and 0.006 for the absolute magnitude distributions respectively, which is tentative evidence that both distributions are not drawn from the same parent sample. However, given the small sample size of only eight high-A_V events, larger samples are required to statistically establish the existence of a difference at higher significance. Of course, both distributions are drawn from the same physical parent sample (GRB hosts), indicating that the different selection criteria probe different host properties.

A possible explanation of the different host properties would be the now on-average higher redshift relative to the Savaglio et al. (2009) sample, where star-formation was driven by more massive galaxies as compared to the more nearby Universe (e.g., Cowie et al. 1996; Hopkins 2004). To test this hypothesis, we selected a subsample from Savaglio et al. (2009) with a median redshift comparable to the hosts in this work. This essentially removes all $z < 1$

Savaglio et al. (2009) hosts and leaves only 13 events for comparison. Despite the small number statistics, the M and M_B values are again placed at the high-mass and high-luminosity end of their respective distribution, and a KS test is also marginally suggestive of a difference (p-values of 0.001 and 0.034 for the masses and absolute magnitudes).

We conclude that by selecting extinguished afterglows we are very likely probing a more luminous, massive and chemically-evolved population of GRB hosts. As these were largely missing from previous samples due to their poor localizations, there is a selection bias and the thus far studied host population is missing most of its massive, evolved and metal-rich members. As a direct consequence, GRB hosts trace the global SFR closer than indicated in studies which are based on host samples of optically selected GRB afterglows, and the apparent deficiency of high-mass host galaxies is at least partially a selection effect.

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