The dark nature of GRB 130528A and its host galaxy

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ABSTRACT

Aims. We study the dark nature of GRB 130528A through multi-wavelength observations and conclude that the main reason for the optical darkness is local extinction inside of the host galaxy.

Methods. Automatic observations were performed at the Burst Optical Observer and Transient Exploring System (BOOTES)-4/MET robotic telescope. We also triggered target of opportunity (ToO) observations at Observatorio de Sierra Nevada (OSN), IRAM Plateau de Bure Interferometer (PdBI) and Gran Telescopio Canarias (GTC + OSIRIS). The host galaxy photometric observations in optical to near-infrared (nIR) wavelengths were achieved through large ground-based aperture telescopes, such as 10.4m Gran Telescopio de Bure Interferometer (PdBI) and Gran Telescopio Canarias (GTC) telescopes. The host galaxy photometric observations in optical to near-infrared (nIR) wavelengths were achieved through large ground-based aperture telescopes, such as 10.4m Gran Telescopio de Bure Interferometer (PdBI) and Gran Telescopio Canarias (GTC) telescopes.

Results. Thanks to millimetre (mm) observations at PdBI, we confirm the presence of a mm source within the XRT error circle that was not detected by the Swift UV/optical telescope (UVOT) or ground-based telescopes at UV/optical/IR wavelengths, but UV/optical/IR emission was not detected in 20-27% of observed GRBs (see also [Melandri et al. 2012], Greiner et al. 2011], despite deep searches during several hours by ground facilities. Events lacking UV/optical/IR emis-

1 http://swift.gsfc.nasa.gov/archive/grb_table/

1 Introduction

Since the launch of the Swift, \(\sim 78\%\) (667/856 as of Apr 1, 2014) of observed Gamma-ray Bursts (GRBs)\textsuperscript{[1]} were detected accurately and rapidly by the Swift X-ray telescope (XRT). Among them \(\sim 73\%\) (488/667) of GRBs were detected by the Swift UV/optical telescope (UVOT) or ground-based telescopes at UV/optical/IR wavelengths, but UV/optical/IR emission was not detected in 20-27% of observed GRBs (see also [Melandri et al. 2012], Greiner et al. 2011], despite deep searches during several hours by ground facilities. Events lacking UV/optical/IR emis-
sion are dubbed “dark GRBs” (Groot et al. 1998) with GRB 970111 being the first such case (Castro-Tirado et al. 1997; Gorosabel et al. 1998).

Currently dark GRBs are defined as those events having no UV/optical afterglow but also a relatively low optical-to-X-ray flux ratio (see Jakobsson et al. 2004 and van der Horst et al. 2009). Plausible causes for dark GRBs, such as observational bias, high level of extinction within the galaxy, Lyman-α cut-off (for high redshift bursts) and intrinsically low UV/optical fluxes are claimed, although a combination of two or three causes is likely (also discussed by Rol et al. 2005; Pyne et al. 2001). The number of well-observed dark GRBs and their hosts is continually being increased thanks to well-targeted ground-based ToO campaigns, which enable us to gain better insight into the nature of GRBs and their environments. Moreover, future space-based missions, Ultra-Fast Flash Observatory (UFFO)-pathfinder/Lomonosov, and UFFO might be helpful to understand the dark nature of GRBs using the early optical follow-up within several seconds after GRB onset (Park et al. 2013; Jeong et al. 2013).

Recent studies have shown that dust extinction inside of the host galaxy might be the probable cause of darkness: the GRB is generated in a denser environment compared with optically bright events (De Pasquale et al. 2003; Perley et al. 2009; Melandri et al. 2012). The prompt properties of dark GRBs at rest frame do not differ with optically bright events, but interestingly, the average X-ray luminosity (unabsorbed X-ray flux at rest frame) of dark bursts is slightly higher, although the observed optical flux is slightly lower (see Fig. 4 in Melandri et al. 2012). A significant correlation between intrinsic X-ray column density and βOX has been pointed out by Canepa et al. (2012), and dark GRBs (βOX < 0.5) Jakobsson et al. 2004 have been shown to have a moderately high column density in comparison to optically bright events.

Host galaxies that harbour dark GRBs are interesting as a study for unbiased samples of star-bursts galaxies in the universe related with SFR (Christensen et al. 2004). Some hosts of dark GRBs trace a sub-population of massive star-burst galaxies, which differ from the main GRB host galaxy population (Kossi et al. 2012). Krühler et al. (2011) report similar results, in that the hosts of the dustiest afterglows have diverse properties but are on average redder, more luminous, and massive in comparison to hosts of optically bright events (see also Hunt et al. 2014). Perley et al. (2013) also deduced similar results by investigating 25 dust obscured Swift GRBs. It suggests that their hosts are more abundant, rather than a small number, compared with un-obscured GRBs at similar redshifts.

On May 28, 2013, at 16:41:23 UT, the Swift Burst Alert Telescope (BAT) triggered and located the “North pole” GRB (D’Elia et al. 2013; Goad et al. 2013). The BAT light curve is multiple-peaked with a duration of about 84 s and exhibited a peak count rate of ~ 5500 counts/s in the 15-350 keV range at ~ 8 s after the trigger. The time-averaged spectrum from T0+0.12 to 79.34 s was fitted by a power law with an exponential cutoff with a photon index 1.39 ± 0.19, E_cutoff (118.3 ± 79.7 keV and total fluence of 5.1 ± 0.2 × 10−2 erg/cm2 in the 15-150 keV band (D’Elia et al. 2013; Cummings et al. 2013). The Swift/XRT began observing the field at 64.9 s after the BAT trigger and found a bright, fading uncatalogued X-ray source (D’Elia et al. 2013). An astrometrically corrected X-ray position was reported later, RA(J2000)=09°18′0.12″ and Dec(J2000)=+87°18′03.7″ with an uncertainty of 1.8 arcsec (radius, 90% confidence, Goad et al. 2013). Initial XRT spectral analysis resulted in a column density of 3.6 ± 0.6 × 1021 cm−2 (90% confidence, Melandri et al. 2013) in excess of the galactic value at 8.5 σ (5.2 × 1020 cm−2; Kalberla et al. 2005), which shows a high equivalent hydrogen column density N_H resembling GRB 051022 (Castro-Tirado et al. 2007). The Swift/UVOT started follow-up observations 75 s after the BAT trigger, however, it did not detect any credible afterglow candidate within the XRT error circle down to 21.7 mag in the white filter (D’Elia et al. 2013; De Pasquale & D’Elia 2013). This encouraged ground-based observations at different wavelengths. The 0.4m telescope at ISON-Kitab Observatory commenced observations 20 min after the BAT trigger with no optical counterpart being reported at a 3 σ limit > 19.1 mag (unfiltered images of 30 s exposure, see Volnova et al. 2013).

In this paper, we discuss the reason for the dark nature of GRB 130528A, using our dataset from the optical to mm wavelengths. The structure of our paper is as follows: in Section 2, we describe our multi-wavelength observations and data reduction. In Section 3, we discuss the observational results, which lead us to consider GRB 130528A as a dark GRB, as well as the host galaxy properties, before summarising our conclusions in Section 4.

2. Observations and data reduction

2.1. Photometric observations in optical/near-infrared wavelength

Following the detection by Swift/BAT and XRT and the non-detection by UVOT, an autonomous search by BOOTES-4/MET was performed prior to a follow-up program with several ground-based telescopes. Early time optical observations were carried out at the BOOTES-4/MET robotic telescope in LiJiang, China (Castro-Tirado et al. 2012), which automatically responded to the GRB alert with observations being conducted on May 28, 17:52:42 UT, which are ~ 1.1 h after the Swift/BAT trigger (T0=16:41:23 UT) in the clear and r-band filters (120 s and 180 s exposures, respectively). The field calibration was achieved using GTC deep observations (see below). We also triggered the 1.5m OSN located in the Sierra Nevada mountain range in the I-band (600 s exposure), and the field calibration was conducted using USNO B1.0 catalogue.

Broadband observations in the optical and nIR for the potential host galaxy were conducted to produce a SED. Observations were performed using various large aperture ground-based telescopes, such as the GTC in r- and i-filters that ranges from ~ 3.4 d to ~ 312 d after the burst. The z-band host galaxy observations were imaged with the 2.0m LT equipped with the the IO:O instrument during three consecutive nights starting on Apr 4, 2014. The z-band field calibration was carried out using the transformation formulas given by Jordi et al. (2006) and the GTC r&i-band secondary standards. A-band observation was conducted with the 6m BTA telescope with SCORPIO located in the Zelenchuksky District on the north side of the Caucasus Mountains in southern Russia. The nIR observations in J and Ks pass-bands using director discretionary time (DDT) were carried out at 4.2m WHT equipped with LIRIS on Dec 23, 2013 with seeing ~ 0.8-1.2′. The field was calibrated using faint standards, FS130 and FS131. The images were reduced, accounting for flat-field and sky background, using the standard method within the IRAF. The bias subtraction was performed automatically at the time of data saving. The log of optical/nIR observations are summarised in Table 1. To determine the photometric magnitudes, we used aperture photometry with the DAOPHOT routine in IRAF.2

http://iraf.noao.edu
Table 1. Photometric observations at the GRB 130528A field at optical/nIR wavelengths. No correction for Galactic extinction is applied.

| Start Time (UT) | T-T_0 (mid days) | Telescope/Instrument | Filter/Grism | Exposure time (seconds) | Magnitude (AB) |
|-----------------|------------------|-----------------------|--------------|-------------------------|----------------|
| May 28, 2013, 17:52:42.438 | 0.050 | BOOTES-4/MET | clear | 120 | >19.7 (3σ) |
| May 28, 2013, 17:54:46.385 | 0.052 | BOOTES-4/MET | Sloan r | 180 | >19.8 (3σ) |
| May 28, 2013, 17:57:50.198 | 0.054 | BOOTES-4/MET | clear | 120 | >19.7 (3σ) |
| May 29, 2013, 20:41:42.640 | 1.167 | 1.5m OSN | I | 600 | >23.0 (3σ) |
| Jun 1, 2013, 03:04:50.211 | 3.409 | 10.4m GTC | Sloan i | 100 × 9 | 22.87 ± 0.08 |
| Jun 1, 2013, 02:41:32.625 | 3.417 | 10.4m GTC | Sloan r | 60 × 3 | 23.28 ± 0.01 |
| Jun 2, 2013, 02:56:40.228 | 4.427 | 10.4m GTC | Sloan i | 100 × 1 | 22.74 ± 0.15 |
| Dec 23, 2013, 05:45:16.011 | 208.554 | 4.2m WHT | J | 9 × 197 | 21.63 ± 0.35 |
| Dec 23, 2013, 06:59:02.247 | 208.610 | 4.2m WHT | K_s | 3 × 432 | 21.43 ± 0.25 |
| Dec 31, 2013, 21:57:12.000 | 217.219 | 6m BTA | B | 300 × 8 | 23.41 ± 0.10 |
| Apr 05, 2014, 22:37:42.667 | 312.247 | 600 s exposures | Sloan z | 300 × 36 | 22.41 ± 0.15 |

2.2. Millimetre observations

Millimetre observations were obtained between ∼ 1.33 d and ∼ 3 d after the GRB onset on May 29, 2013 and Jun 02, 2013, via our on-going ToO program at PdBI in the French Alps (Guilloteau et al. 2013) and 1.8 arcsec (Goad et al. 2013) radius, respectively. The ellipse C shows the mm detection beam size by PdBI (see Sect. 2.2 in this paper). It clearly points out the putative host galaxy of GRB 130528A by confirming a mm afterglow with a signal-to-noise ratio of ∼ 4 (at 86.7 GHz). The measured i-band magnitude is 22.87 ± 0.08 in AB system.

3. Results and discussions

3.1. No optical/nIR afterglow detections and host galaxy observations at the optical/nIR wavelengths

No plausible optical/nIR transient was detected down to 19.7 mag (T-T_0+1.1 h, clear) at BOOTES-4/MET and 23.0 mag (T-T_0+1.17 d, J-band) at 1.5m OSN telescopes. The potential host galaxy was first revealed using our on-going ToO program at 10.4m GTC in the Sloan r and i-bands and is shown in Fig. 1. It has 22.9 mag in the i-band and 23.3 mag in the r-band. The z-band brightness is revealed with 22.4 mag by LT. The nIR data was reduced under the IRAF routine and resulted in magnitudes of 21.6 mag and 21.4 mag in J and K_s, respectively. The BTA B-band observation gave a magnitude of 23.4 mag. All magnitudes are given in Table 1 and are presented in the AB system (vega to AB offset is following Fukugita et al. 1995).

3.2. Afterglow detection at mm

From the mm observations between ∼ 1.33 d and ∼ 3 d after the GRB, we clearly confirm a mm afterglow with a signal-to-noise ratio of ∼ 4 (at 86.7 GHz) at the position of the putative host galaxy, thus confirming the association. The mm source was not detected in the second dataset, implying a signific-

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3 http://www.iram.fr/IRAMFR/GLIDAS
Table 2. mm afterglow flux densities measured at the Plateau de Bure Interferometer.

| Start Time (UT) | End Time (UT) | Configuration | Flux density [mJy] | Frequency [GHz] |
|----------------|---------------|---------------|------------------|-----------------|
| May 29, 2013, 23:33 | May 30, 2013, 01:42 | 5Dq | 0.38 ± 0.10 | 86.7 |
| Jun 02, 2013, 13:13 | Jun 02, 2013, 15:03 | 5Dq | < 0.07 ± 0.09 | 86.7 |

Fig. 3. The SED of GRB 130528A afterglow at 1.33 days. A model is overplotted with the observed data, assuming \( \nu_s = 1.1 \times 10^9 \text{ Hz} \), \( \nu_a = 1.1 \times 10^{12} \text{ Hz} \), \( \nu_c = 6 \times 10^{16} \text{ Hz} \), \( F_{nu_a} = 700 \mu \text{Jy} \), \( p = 2.2 \), and a smoothing parameter \( s = 3 \) in the case of the ISM model \( \nu_a < \nu_c < \nu_s \). The red arrows represent observed flux in the radio and X-ray at 1.33 days. The blue arrow shows the \( I \)-band upper limit observed by 1.5m OSN at a similar epoch. The low upper limit can be explained by a significant extinction in the line-of-sight.

3.3. Predicted optical brightness from the afterglow SED

We determined the expected brightness for the optical afterglow by following the standard fireball model (Sari et al. 1998). At the time of the radio observation by the PdBI, i.e., \( T = 1.33 \) d, we took the X-ray flux at a similar epoch from the XRT light curve. The overplot of the afterglow SED model (see Fig. 3) was constructed assuming the following parameters: \( \nu_s = 1.1 \times 10^9 \text{ Hz} \), \( \nu_a = 1.1 \times 10^{12} \text{ Hz} \), \( \nu_c = 6 \times 10^{16} \text{ Hz} \), \( F_{nu_a} = 700 \mu \text{Jy} \), \( p = 2.2 \), and a smoothing parameter \( s = 3 \) in the slow cooling regime (Sari et al. 1999), showing the best overlap to the observed mm and X-ray data. We also constrained the parameters of the blast wave as \( E_b = 10.9 \times 10^{53} \text{ erg} \), \( n = 0.004 \text{ cm}^{-3} \), \( \epsilon_e = 0.02 \), and \( \epsilon_b = 0.01 \) by the assumed model parameters using equations 27-30 of Wijers & Galama (1999). We checked the appropriateness of \( p \) using the time sliced XRT spectrum tool on the timescale that displays less spectral evolution, such as \( T = 0.02 \text{ to } 0.3 \text{ days} \), resulting in a large uncertainty in \( p \). Therefore, we used a universal value of \( p = 2.2 \) for the energy distribution of the electrons. The XRT spectral tool also gave a intrinsic value for excess absorption to be \( N_L = 3.7 \times 10^{21} \text{ cm}^{-2} \). The modelled SED can be used to estimate the amount of extinction by dust in the line-of-sight. The predicted magnitude in \( I \)-band at \( T = 1.33 \) days is \( -20.4 \) mag (vega), and the upper limit produced by 1.5m OSN was \( 22.5 \) mag (vega). Therefore, it implies a minimum extinction \( A_{I,m} = 0.8 \text{ mag} \) \( (A_{V,m} = 0.9) \) at rest frame (after galactic extinction correction by Schlafly & Finkbeiner 2011). Another independent measurement of the expected UV/optical extinction can be obtained from the X-ray absorption to dust-extinction ratio, \( N_{H,X}/A_V \), following Schady et al. (2010). The X-ray absorption \( N_{H,X} \) of GRB 130528A with rest frame, which is produced using the “zTBabs” model within Xspec (Evans et al. 2009), is \( N_{H,X} = 2.79 \pm 2.61 \times 10^{22} \text{ cm}^{-2} \). Using the mean values of \( N_{H,X}/A_V = 3.3 \times 10^{22}, 3.4 \times 10^{22} \text{ and } 2.1 \times 10^{22} \text{ cm}^{-2} \) for the different extinction models (Small Magellanic Cloud (SMC), Large Magellanic Cloud (LMC), and Milky Way (MK)), see Schady et al. (2010), \( A_V \) was found to be 0.84, 0.82, and 1.32 mag for SMC, LMC, and MW, respectively. These values are consistent with the previous findings from the afterglow SED.

3.4. Redshift determination and the star-formation rate

The single emission line at 8500Å in the GTC spectra likely corresponds with \([OII] 3727Å\) at a redshift \( z = 1.250 \pm 0.001 \), how-

Fig. 4. The SED of GRB 130528A host galaxy in the B,r,i,z,J, and K_s bands. The AB magnitudes are corrected considering for the Galactic extinction \( E(B-V) = 0.144 \) (Schlafly & Finkbeiner 2011). The thick line shows the best fit \((c^2/d.o.f. = 0.364)\) achieved with \( z_H = 0 \), a stellar population with an age of 2.6 Gyr, \( M_B = -21.16 \), and Solar metallicity. The rest of the lines show the evolution of the SED fit when \( A_V \) increases gradually from 0 to 0.8. As seen, the fit gets worse when \( A_V \) grows.

4 http://www.swift.ac.uk/xrt_spectra
ever, due to the low SNR of the spectrum, the 1D projection of the optical spectrum could not be extracted. The [OII] line in 2D analysis could not be extracted due to the low SNR of the spectrum. The [OII] line in 3D was also not detected. 

3.5. The host galaxy spectral energy distribution

Broadband observations were matched using the Hyperz code (Bolzonella et al. 2000) to synthetic SED templates based on the GISSEL 98 library (Bruzual & Charlot 1993). The time evolution of the SFR for each template is represented by an exponential model, which is SFR = exp(-t/τ), where τ is the SFR timescale. Eight values of τ were explored (0.1, 0.2, 0.3, 0.5, 1.5, 3.0, and 5.0 Gyr) and the initial mass function (IMF) given by Miller & Scalo (1979) was assumed. The impact of the metallicity (which is expected to be minor, as tested by Bolzonella et al. 2000) to synthetic SED templates based on the GISSEL 98 library (Bruzual & Charlot 1993). The time evolution of the SFR for each template is represented by an exponential model, which is SFR = exp(-t/τ), where τ is the SFR timescale. Eight values of τ were explored (0.1, 0.2, 0.3, 0.5, 1.5, 3.0, and 5.0 Gyr) and the initial mass function (IMF) given by Miller & Scalo (1979) was assumed. 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