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LETTER

Letter to the Editor

Optical and near-infrared follow-up observations of GRB980329

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Abstract. We imaged the field of GRB980329 in the optical and in the near-infrared starting 20 hours after the event, at the ESO NTT, at the NOT, at the APO and at the TIRGO. In the first night we detect an object of $R = 23.6 \pm 0.2$ within the BeppoSAX NFI error box at the same position as a transient VLA source proposed as the radio afterglow of this GRB. The source faded by 1.6 ± 0.5 magnitudes in 2.1 days, similarly to the decays of previous GRB optical afterglows. This transient is likely the optical counterpart of GRB980329. In the near-infrared we detect signal at 2-σ significance, whose position is only marginally consistent with that of the VLA source. The spectrum of the transient bears the signatures of substantial absorption within the GRB host galaxy. The afterglow energetics are interpreted as synchrotron radiation from an expanding blast wave.

Key words: gamma-rays: bursts – radiation mechanisms: non thermal

1. Introduction

The Gamma Ray Burst GRB980329 was detected on March 29.1559 UT with the BeppoSAX Gamma Ray Burst Monitor (GRBM) and Wide Field Cameras (WFC) unit number 2 (in 't Zand et al. 1998), and with BATSE (Briggs et al. 1998). The burst, rapidly localized by the WFC with a $3'$ radius accuracy, was outstandingly bright in γ-rays (peak intensity of $\sim$6000 counts s^{-1} and fluence of 5.5×10^{-5} erg cm^{-2}, 40–

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700 keV) and X-rays (∼6 Crab, 2–26 keV). Observations with the BeppoSAX Narrow Field Instruments (NFI) started on March 29.449 UT revealed an unknown fading X-ray source in the WFC error box which has been identified as the GRB X-ray afterglow (in 't Zand et al. 1998). Here we report on optical and near-infrared imaging at the 3.5m ESO New Technology Telescope (NTT, La Silla, Chile), at the 2.5m Nordic Optical Telescope (NOT, La Palma, Canary Islands), at the ARC 3.5m telescope of the Apache Point Observatory (APO, Arizona) and at the 1.5m Gornergrat Infrared Telescope (TIRGO, Switzerland).

2. Observations and Results

2.1. Optical

We observed GRB980329 at the NTT with EMMI in V and R band filters, at the NOT with ALFOSC in R and I band filters, and at the APO with SPICam in the R band filter (see Table 1 and also Reichart et al. 1998). The images have been debiased and flat-fielded following a standard procedure. PSF-fitting photometry was done using the DAOPHOT II package (Stetson 1987) within MIDAS. The R and V band exposures were calibrated using NTT images of the Landolt field PG1047+003 (Landolt 1992), for which we adopted airmass extinction coefficients 0.07 and 0.11, respectively. No calibration image is available in the I band. Table 1 reports a summary of all the known optical and near-infrared calibrated observations in the first 10 days after the GRB. In the NTT R band image of March 29.99 we clearly detect an unresolved object (Fig. 1a) with $R = 23.6 \pm 0.2$ at the position RA = 07h 02m 38s, Dec = +38° 50′ 44″.1 (J2000), coincident (within the astrometric errors of 0″.4) with the transient radio source VLA J0702+3850 (Taylor et al. 1998), proposed as the radio afterglow of GRB980329, and with the galaxy observed by Djorgovski et al. (1998a) on April 2, tentatively identified with the host galaxy of the radio counterpart. The source is no longer visible in the NTT R band images of the subsequent nights, down to a limiting magnitude of $R = 24$. Although the source is not detected in the NOT R band frames of individual nights, the sum of the images of March 30.93 and 31.87 (corresponding to the fiducial average UT of March 31.4, Fig. 1b) shows an object of $R = 25.0 \pm 0.5$. In the APO R band image the transient is well detected with $R = 25.2 \pm 0.3$ (Fig. 1c), indicating that the source decayed by 1.6 ± 0.5 magnitudes in 2.1 days. The object is no longer detected in the NOT R band exposures of April 1.95 down to a limiting magnitude of $R = 25.5$. The source is not detected in the V and I bands.

2.2. Near-infrared

J band images of the GRB980329 field were obtained at the TIRGO with the ARNICA NICMOS 3 array detector (256x256 pixels). With the $4' \times 4'$ field of view detector the error box was covered with a mosaic of frames. Standard data reduction was performed using the IRAF procedures in the ARNICA reduction package. In the final J band image, calibrated using star SAO042804 (Hunt et al. 1998), no object is detected at the position of the optical/radio transient down to J = 20.7 (1-σ). However a 2-σ signal at J = 20.05 is detected at RA = 07h 02m 38.13s, Dec = +38° 50′ 41″.9 (J2000), 2″.3 ± 1″.0 away from the radio transient, not associated with any other object detected in either the optical or the K band. Given the photometric and positional uncertainties, we cannot establish the association of this source with the GRB.

Table 1. Log of optical and near-infrared observations

Date (UT)	Telescope	t[a]	Magnitude[b]	Ref.
Mar 29.83	Teramo		$R_c > 20$	1
Mar 29.85	BUT, JKT		$R_c > 22$	2
Mar 29.85	TIRGO	660	$J > 19.9$[c]	3
Mar 29.9	Asiago		$R_c > 21$	4
Mar 29.9	TLST		$R_c > 22$	5
Mar 29.92	OGS		$R_c > 21$	6
Mar 29.99	NTT	1200	$V > 23.5$	3
Mar 29.99	NTT	1200	$R_c = 23.6 \pm 0.2$	3
Mar 30.0	88″ Hawaii		$R_c > 22.3$	7
Mar 30.9	BUT, JKT		$R_c > 22$	2
Mar 30.93	NOT	1200	$R_c > 25.3$	3
Mar 30.99	NTT	1200	$V > 23.5$	3
Mar 30.99	NTT	1200	$R_c > 24$	3
Mar 31.0	88″ Hawaii		$R_c > 23$	7
Mar 31.5	OAN, JKT		$R_c > 22$	2
Mar 31.87	NOT	1200	$R_c > 25.3$	3
Apr 1.01	NTT	1200	$V > 23.5$	3
Apr 1.01	NTT	1200	$R_c > 24$	3
Apr 1.125	APO	3600	$R_c = 25.2 \pm 0.3$	3
Apr 1.17	WIYN		$R_c > 24.2$	8
Apr 1.21	APO		$J > 20.9$	9
Apr 1.95	NOT	1800	$R_c > 25.5$	3
Apr 2.0	Keck-II		$R_c = 25.7 \pm 0.3$	10
Apr 2.0	Keck-I		$K = 20.7 \pm 0.2$	11
Apr 3.0	Keck-I		$K = 20.9 \pm 0.2$	11
Apr 3.1	WIYN		$R_c > 23.9$	8
Apr 6.27	Keck-I		$K = 21.4 \pm 0.2$	12
Apr 8.28	Keck-I		$K = 21.9 \pm 0.4$	12

[a] Exposure time in seconds.
[b] Errors and upper limits are 1-σ.
[c] 2-σ upper limit.

References: [1] Brocato et al., 1998; [2] Guarnieri et al., 1998; [3] This paper; [4] Cappellaro, 1998; [5] Klose et al., 1998; [6] Corradi et al. 1998; [7] Djorgovski et al., 1998a; [8] Schaefer, 1998; [9] Cole et al., 1998; [10] Djorgovski et al., 1998b; [11] Larkin et al., 1998; [12] Metzger et al., 1998.

3. Discussion

The optical transient lies within the 1′ NFI radius error box of the X-ray afterglow. Fitting a power-law to the R band flux decay, $f(t) \propto t^{-\alpha}$, we find $\alpha = 1.3 \pm 0.2$. This is consistent with our non-detection of any source brighter than $R = 25.5$ in April 1.95 and the non-detection by Guarnieri et al. (1998). An index $\alpha \sim 1.3$ is also consistent with the fading observed by Klose et al. (1998) in the I band, and with our (uncertain) J band mea-

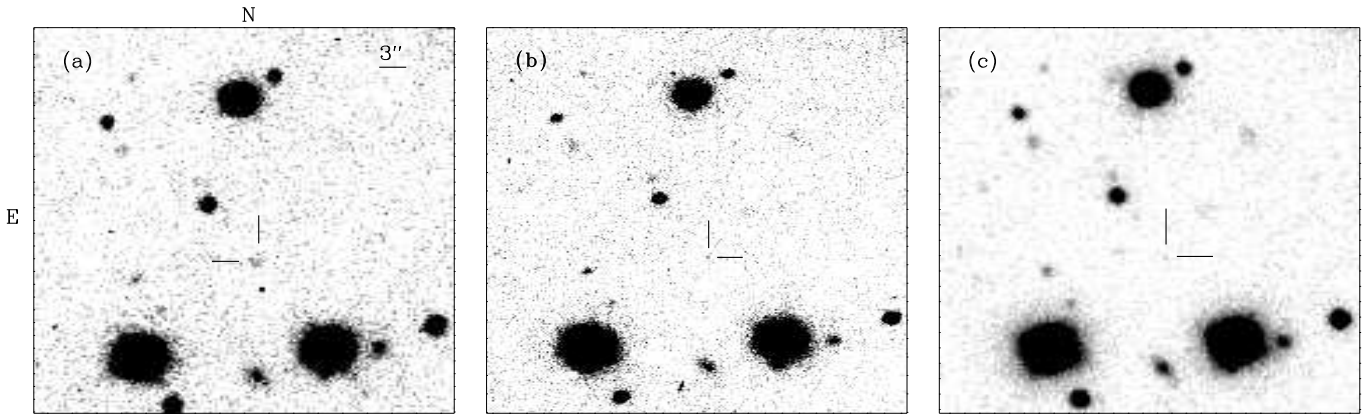

Fig. 1. a NTT R band image of March 29.99 UT: the indicated object, at $R = 23.6 \pm 0.2$, is the proposed optical counterpart of GRB980329; **b** sum of the R band exposures taken at the NOT on March 30.93 and 31.87; the object is still visible though fainter; **c** APO R band image of April 1.125; the object has faded to $R = 25.2 \pm 0.3$

surement together with the limit $J > 20.9$ on April 1.2 (Cole et al. 1998). This decay is similar to that observed in other energy ranges (K band, Larkin et al. 1998; sub-mm, Smith & Tilanus 1998; X-rays, in 't Zand et al. 1998) and to the decays of previous optical afterglows of GRBs ($\alpha \simeq 1 \div 2$, van Paradijs et al. 1997, Fruchter et al. 1998, Galama et al. 1998, Diercks et al. 1998, Groot et al. 1998). We conclude that the transient object is the fading counterpart of the GRB980329. Extrapolating the power-law to the time of the Keck observations by Djorgovski et al. (1998b) yields a magnitude consistent with the one they report for the putative host galaxy ($R = 25.7 \pm 0.3$). This suggests that the optical transient could still contribute a significant fraction of the total observed flux at that time.

Since GRB980329 and GRB970508 are the only two GRBs so far with radio and mm counterparts we have compared their radio-to-X-ray spectral energy distributions (SEDs, νf_ν) at different epochs (Fig. 2) with the multi-wavelength afterglow model of Sari et al. (1998). For GRB970508 the epochs correspond to the start of rise to optical maximum (May 9.9); to the optical maximum (May 10.8); to the last upper limit determination in the sub-mm band (May 16.9); to the first sub-mm detection (May 19). For GRB980329, the chosen epochs correspond to the first R band detection (March 29.99) and to the second sub-mm detection (April 6.2). The data (see figure caption for references) have been corrected for the interstellar extinction within the Galaxy, $A_V = 0.09$ for GRB970508 (Djorgovski et al. 1997), $A_V = 0.4$ for GRB980329 (Rowan-Robinson et al. 1991). We adopted the Galactic extinction curve of Cardelli et al. (1989). The X-ray data of GRB970508 on May 16.9 and 19 are extrapolated in time according to the power-law used to model the X-ray light curve (Piro et al. 1998). For the SED of GRB980329, the point at 8.46 GHz at the second epoch is the average of the three measurements of Taylor et al. (1998). We made a rough calibration of the March 29.9 I band data (Klose et al., 1998) by a power-law extrapolation of the R and V band data, inferred from the March 29.99 NTT images, of a nearby object that appears to be equally bright as the transient in the I band image. From this we infer that the GRB should have $I \simeq 21.5$ on March 29.9, which, when scaled to March 29.99 according to a power-law of index 1.3, yields $I \simeq 21.7$. We assigned to this value a conservative error of ~ 0.7 magnitudes, to account for the uncertainties in spectral slope, temporal extrapolation and eye estimate of the relative I band fluxes of the two objects in Klose et al.'s images. For the second epoch, we used the magnitude of the host galaxy, $R = 25.7$, as an upper limit on the level of the transient. In fact, all optical and near-infrared fluxes of the point-like source might be overestimated, due to the underlying host galaxy, the brightness of which is not precisely determined in any band. The X-ray flux at 4 keV on March 29.99 has been computed using a temporal power-law of index $\alpha = 1.5 \pm 0.2$ and a spectral index $\beta = 1.4 \pm 0.4$ (in 't Zand et al. 1998; $f_\nu \propto \nu^{-\beta}$).

The I band detection of Klose et al. (1998), roughly calibrated by us, and our R band measurement on March 29.99 (see Table 1) yield a color $R - I \sim 2$, equivalent to a spectral index of ~ 5, which suggests a red spectrum for the transient. Similarly, the measurements in April 2 (Table 1) give $R - K \gtrsim 5$, corresponding to $\beta \gtrsim 3$. These spectral slopes are much steeper than found for GRB970508, for which spectroscopy (Metzger et al. 1997) and multi-band photometry (see caption to Fig. 2 for references) give an optical index of $\beta \simeq 1$ and an optical-to-near-infrared index of $\beta \simeq 0.5$. Moreover, the blast wave models of GRB afterglows predict flatter indices in these bands ($\beta \simeq 0.5 \div 1.5$, see Sari et al. 1998, Wijers & Galama 1998). Since the dust column density in the direction of GRB980329 is moderate, reddening could be due either to intrinsic or intergalactic extinction. The former would imply the presence of a dust and gas rich medium and likely intense star formation, while the latter would suggest a rather high redshift. The remarkable intensity of the burst does not point to a very large distance (see also in 't Zand et al. 1998), therefore we have considered the possibility that GRB980329 occurred in a starburst galaxy, and we have investigated how the typical obscuration of this class of galaxies would affect the intrinsic spectrum of GRB980329 at a range of redshifts up to $z \sim 2$. To this aim, we corrected the SED of GRB980329 for the redshifted extinction curve of 19

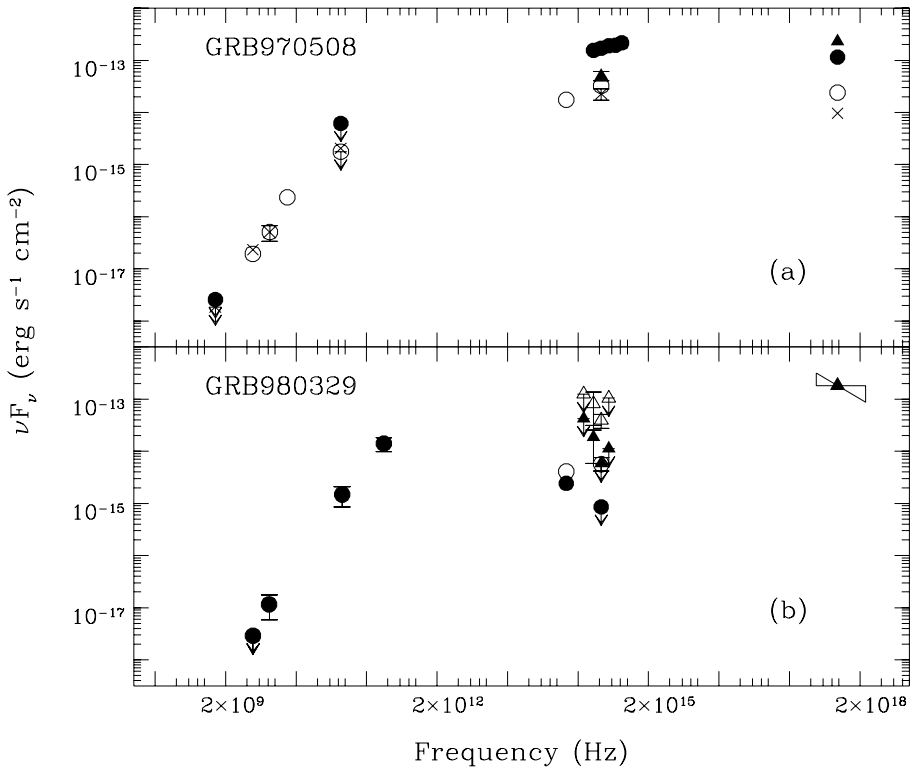

Fig. 2a and b. Comparison of multi-wavelength energy distributions of GRBs 970508 and 980329 corrected for the Galactic extinction (see text). **a** Energy spectrum of GRB970508 in May 9.9 (filled triangles); May 10.8 (filled circles); May 16.9 (open circles); May 19 (crosses). Data are from Piro et al. (1998, X-ray); Galama et al. (1998, U photometry); Sokolov et al. (1998, $BVRI$); Castro-Tirado et al. (1998, R); Pedersen et al. (1998, R); Morris et al. (1997, K); Bremer et al. (1998, mm); Frail et al. (1997, radio). Error bars have been omitted when smaller than the symbol size. **b** Same as **a** for GRB980329 in March 29.99 (filled triangles) and April 6.2 (filled circles). Data are taken from in 't Zand et al. (1998, X-ray; the slope of the BeppoSAX MECS spectrum is reported along with its 1-σ confidence range); Smith & Tilanus (1998, mm); Taylor et al. (1998, radio). See Table 1 for references to the optical and near-infrared photometry. Data corrected for typical intrinsic obscuration within starburst galaxies at $z = 1$ are also reported as open triangles for March 29.99 and open circles for April 6.2

local starburst galaxies (Calzetti 1997). Since the curve has been derived by considering only the starburst regions, excluding the old stellar populations of the sample galaxies, we expect it to be appropriate also for starburst galaxies at moderate or high redshift (Calzetti 1998). For $z \simeq 1$ the corrected R band upper limit and K band flux of April 6.2 imply a spectral index $\beta \geq 0.7$, more consistent with theoretical expectation (see Fig. 2b). This redshift value is in agreement with the observation of intense star formation at $z \sim 1$ (Madau et al. 1996) and thus broadly supports the proposal that GRBs occur in actively star-forming galaxies (Paczyński 1998). The visual extinction of the applied model ($A_V = 1.2$) would correspond to $N_H = 1.9\times10^{21}$ cm^{-2} in our Galaxy (and therefore to a probably not higher value in a starburst), consistent within 2-σ with the N_H derived from the power-law fit to the X-ray data (in 't Zand et al. 1998).

The overall SEDs of the two afterglows at the different epochs are consistent with a single emission component, whose maximum shifts in time toward lower energies. For GRB970508, the SED appears smooth and exhibits a broad peak which, at the first epoch, likely falls at or immediately above X-ray frequencies, while it is located between 10^{14} and 10^{16} Hz on May 19. In GRB980329, the peak of the νf_ν curve on March 29.99 is between 10^{17} and 10^{18} Hz, as indicated by the X-ray spectral index, while on April 6.2 it is located around 10^{13} Hz and appears narrower. However, the multi-wavelength data are too few and sparse to allow a detailed description of the spectral shapes in the various bands and precise localization of the energy peaks. In particular, no X-ray flux is available for GRB980329 in April 6.2, nor could it be reliably derived from the earlier measurement (the significant time separation between the two epochs prevents an extrapolation of the temporal power-law fitted to the X-ray afterglow). According to the Sari et al. model, in which the emission is produced through synchrotron radiation from an expanding relativistic shell, it is possible to reproduce the observed temporal evolution of the multi-wavelength spectrum of GRB970508 for a relativistic electron distribution $N(\gamma) \propto \gamma^{-p} d\gamma$ with $p \gtrsim 2$. (Note that the representation of the synthetic spectrum in their Fig. 1 is in f_ν.) On the other hand, the SED peak of GRB980329, which is much better constrained than that of GRB970508, exhibits a displacement by 4 decades in energy or more in $\sim$10 days. This cannot be accounted for by the Sari et al. model, even assuming the fastest temporal evolution envisaged by their scenario (fully radiative expansion in fast cooling regime, which holds anyway only within short

times after the GRB). The onset of a subrelativistic expansion some days after the GRB would imply a faster change of the synchrotron break frequency of the electron distribution (Wijers et al. 1997) and might better describe the observed behaviour.

The hypothesis of significant intrinsic obscuration at $z \sim 1$ for GRB980329 improves the modeling of its multi-wavelength data, although it does not account for its apparently more abrupt spectral evolution than observed for GRB970508. Under this assumption, which by no means represents a stringent prediction on the redshift, we estimate that the total energy released by the GRB in the observed 40–700 keV range would be approximately 3×10^{52} erg ($H_0 = 65$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$), consistent with models of GRB formation from coalescence of neutron stars.

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