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Constraints on short gamma-ray burst models with optical limits of GRB 050509b[1]

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ABSTRACT

We have obtained deep optical images with the Very Large Telescope at ESO of the first well-localized short-duration gamma-ray burst, GRB 050509b. We observed in the *V* and *R* bands at epochs starting at $\sim$ 2 days after the GRB trigger and lasting up

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to three weeks. We detect no variable objects inside the small *Swift*/XRT X-ray error circle down to 5σ limiting magnitudes of $V = 26.5$ and $R = 25.2$. The X-ray error circle includes a giant elliptical galaxy at $z = 0.225$, which has been proposed as the likely host of this GRB. Our limits indicate that if the GRB originated at $z = 0.225$, any supernova-like event accompanying the GRB would have to be over 100 times fainter than normal Type Ia SNe or Type Ic hypernovae, 5 times fainter than the faintest known Ia or Ic SNe, and fainter than the faintest known Type II SNe. Moreover, we use the optical limits to constrain the energetics of the GRB outflow, and conclude that there was very little radioactive material produced during the GRB explosion. These limits strongly constrain progenitor models for this short GRB.

Subject headings: gamma rays: bursts — supernovae

1. Introduction

While it is now well established that long-duration γ-ray bursts (GRBs) coincide with the explosions of massive stars leading to very energetic core-collapse supernovae (SNe) (MacFadyen & Woosley 1999; Bloom et al. 1999; Stanek et al. 2003; Hjorth et al. 2003), the origin of the short GRB population, characterized as having short durations (< 2 s) and hard spectra (Kouveliotou et al. 1993), remains unknown. There have been as yet no afterglow detections in the very few cases where searches for optical counterparts of short GRBs were performed, primarily due to the lack of early and precise localizations (Kehoe et al. 2001; Gorosabel et al. 2002; Hurley et al. 2002; Klotz, Boër & Atteia 2003).

Recently, the *Swift* satellite (Gehrels et al. 2004) provided the first rapid and accurate X-ray localization of a short/hard GRB, opening the window for rapid progress on the origin of short GRBs. GRB 050509b (Gehrels et al. 2005) was detected on 2005 May 09 at 04:00:19.23 (UT) by the *Swift* Burst Alert Telescope (BAT). It was a short (40 ms) and fairly hard burst. The *Swift* X-ray Telescope (XRT) slewed and started observing the burst only 62 seconds after the BAT trigger; an initial source location with error circle radius, $r = 6.''0$, was reported 2.5 hours later and was subsequently refined to R.A. = $12^{\rm h}\ 36^{\rm m}\ 13.58^{\rm s}$, decl. = $+28^\circ\ 59'\ 01.3''$ (J2000, $r = 9.''3$, Gehrels et al. 2005).

The error region of GRB 050509b was observed by several groups (see, e.g., Bloom et al. 2005; Gehrels et al. 2005; Cenko et al. 2005). Remarkably, the burst error circle overlaps with a

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[1] Based on observations collected at the European Southern Observatory, Paranal, Chile (ESO Programme 075.D-0261).

giant elliptical galaxy, 2MASX J12361286 + 2858580 (hereafter G1) at $z = 0.225$ (see Fig. 1 and Bloom et al. 2005), belonging to the cluster of galaxies ZwCl 1234.0+2916 = NSC J123610+285901 (Zwicky & Herzog 1963; Gal et al. 2003). The *a posteriori* probability of a chance alignment of a GRB and such a giant elliptical galaxy is $\sim 10^{-4}$. Assuming that the elliptical galaxy is therefore the host galaxy, Bloom et al. (2005) and Gehrels et al. (2005) argued that a likely origin of GRB 050509b is a neutron star (NS)-NS or NS-black hole (BH) merger.

It should be noted that a merger does not necessarily imply the absence of optical or other long-wavelength phenomena after the GRB. For example, the ‘mini-SN’ model (Li & Paczyński 1998) predicts a bright optical flash of much shorter duration than the one from a ‘normal’ SN, typically of about one day. But there are alternative scenarios for the origin of short GRBs. Zhang, Woosley & MacFadyen (2003) have suggested that short GRBs may be a variant of long GRBs, e.g., ‘collapsar’-like events leading to stripped-core, core-collapse SNe, much like those seen in conjunction with long GRB afterglows (see also Ghirlanda, Ghisellini & Celotti 2004; Yamazaki, Ioka & Nakamura 2004). We note that two of the three spectroscopically confirmed long GRB-SN associations to date (GRB 980425/SN 1998bw at $z = 0.0085$ and GRB 031203/SN 2003lw at $z = 0.106$) were detected in the optical because of their very strong Type Ic SNe rather than their afterglows (Galama et al. 1998; Prochaska et al. 2004; Malesani et al. 2004; Thomsen et al. 2004). An alternative suggestion is that short GRBs are related to thermonuclear explosions, leading to Type Ia SNe (Dar & De Rujula 2004; Dado, Dar & De Rujula 2005). Finally, Germany et al. (2000) even suggested that the peculiar Type II SN SN 1997cy was related to the short GRB 970514 based on their temporal and spatial coincidence. It is obvious from the above, that a search for a SN associated with GRB 050509b would help constrain both the energetics of short GRBs and, possibly, their progenitor models (Fan et al. 2005).

We have, therefore, obtained deep images of the XRT error circle at the expected peak time of the putative SN, as well as early images for comparison. In this Letter we present our observations and analysis (§ 2) and discuss the constraints these set on short GRB energetics and progenitor models (§ 3). A cosmology with $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_\mathrm{m} = 0.3$, and $\Omega_\Lambda = 0.7$ is assumed throughout this Letter.

2. Observations and data analysis

We obtained deep V and R band images containing the XRT error circle with the FORS1 and FORS2 instruments at the ESO 8.2-m Very Large Telescope (Kueyen and Antu, respectively) at several epochs (Table 1). The data obtained on 8 and 13 days after the GRB trigger were strongly affected by the proximity of the Moon. Consequently, our deepest images were obtained during the first and last sets of observations (i.e., at a few days and ~ 3 weeks after the GRB).

The data were reduced in a standard way, including overscan correction, bias subtraction, and flatfielding using skyflats obtained in the morning. Photometric calibration was achieved using known FORS2 zero points and checked against the SDSS and photometry of the field obtained at the Tautenburg observatory. We estimated the limiting magnitudes in the fields of the obtained images by doing photometry on a large ($\sim$ 50) number of objects in these frames. We used the `IRAF` task `phot` with an aperture of twice the seeing disk, and obtained the 3σ limiting magnitudes given in Table 1 from the errors on the derived magnitudes.

The first image, obtained 1.85 days after the burst, revealed a large number of very faint objects, as well as G1, inside the XRT error circle (see Fig. 1 and Hjorth et al. 2005; Gehrels et al. 2005; Bloom et al. 2005). As the entire error circle is affected by light from G1, we proceeded with (i) galaxy fitting and subtraction and (ii) difference imaging, to look for faint and variable sources.

To fit the smooth light distribution of G1, the surface area around the galaxy was divided into annuli of increasing widths centered on the nucleus of the galaxy. A robust fitting technique was used to fit a harmonic series to pixel values within each of the annuli. The full model was obtained by cubic spline interpolation between the harmonic coefficients in the radial direction. Finally the smooth model was subtracted from the galaxy image (Fig. 1) enabling a search for objects previously hidden by G1. In the subtracted image we only detect one new faint ($V \sim 26$) object inside the XRT error circle, about $2\farcs7$ northeast of the G1 galaxy center. This object does not appear to be variable (see below). We conservatively estimate that sources brighter than $V \gtrsim 26.7$ and $R \gtrsim 25.7$ would have been detected in these images. However, no other object brighter than the already known sources (Bloom et al. 2005) is present inside the XRT error circle in our first or last epoch images.

To search for a variable object we also subtracted the early images from the late images in the same bands. The images were aligned, the sky background subtracted, and the images scaled to the same brightness level. We also convolved the image with the best seeing with a spatially variable kernel to match the inferior seeing of the other image, according to the method outlined in Alard & Lupton (1998). This provided very clean subtractions, except for near the center of the galaxy (Fig. 1). No variable sources were detected.

To determine how bright an object could be hidden by the G1 galaxy we constructed a point-spread function (PSF) from stars in the field and added artificial stars of varying magnitude inside the galaxy before the image subtraction. For the V-band, after differencing the first and last epochs, we could clearly detect fake objects of $V \simeq 26.5$ in the subtracted frame. Photometry on the subtracted frame showed these detections to be at the 5σ level. The R-band subtraction provided somewhat poorer limits of $R \simeq 25.2$, at the 5σ significance level. In the very nucleus of G1, the galaxy subtraction is poor and we can only detect a source of $V \sim 24$. In conclusion, our analysis shows no new or variable object within the XRT error circle down to $V \simeq 26.5$ or $R \simeq 25.2$; these limits do not apply, however, for the nucleus of G1.

3. Discussion

We plot the limits derived in § 2 in Fig. 2 along with a number of SN lightcurves as they would appear at $z = 0.225$. The Type Ia templates are from Nugent's compilation[2] and include (i) a template of a normal Type Ia SN (Nugent, Kim & Perlmutter 2002) and (ii) a template based on the very sub-luminous Type Ia supernovae SN 1991bg and SN 1999by. The Type Ic SNe plotted are (iii) the very energetic Type Ic SN 1998bw associated with the long GRB 980425 (Galama et al. 1998) and (iv) the faint, fast-rise Type Ic SN 1994I (Richmond et al. 1996), which was not associated with a GRB but provides a good fit to the lightcurve bump in XRF 030723 (Fynbo et al. 2004). Figure 2 clearly demonstrates that even the faintest of these SNe would have been detected at the time of our observation at a level $\sim$ 1.8 mag brighter than our limit (or more than 5.2 mag fainter than a SN like SN 1998bw).

Type II SNe come in various flavors, the faintest of which are Type IIP. Our limit of $V = 26.5$ translates into a limit of M_B of -13.3 at $z = 0.225$. All the SN peak magnitudes included in Richardson et al. (2002) are brighter than this magnitude, including the faintest Type IIP SNe.

From the above we conclude that if GRB 050509b were associated with a normal SN, its host galaxy must either be at a high redshift ($z \gtrsim 1.2$), consistent with the constraints on the redshifts of the faint galaxies in the XRT error circle (see Bloom et al. 2005) or, if it indeed is at $z = 0.225$, its SN light must have been extinguished by dust along the line of sight. The latter option appears unlikely as G1 is an elliptical galaxy with very little star formation (Bloom et al. 2005; Gehrels et al. 2005) and the likely background sources do not appear strongly reddened. We can therefore conclude that there was no SN of known type and characteristics associated with GRB 050509b if it occurred in G1. However, there remains a (small) probability that GRB 050509b is at a much higher redshift than the cluster and is gravitationally lensed by G1, since the predicted Einstein radius of G1 ($r = 3\farcs3$) overlaps the XRT error circle (Engelbracht & Eisenstein 2005).

The absence of a SN rules out models predicting a normal SN Ia associated with short GRBs (Dar & De Rujula 2004; Dado, Dar & De Rujula 2005). Likewise, our observations disfavour a GRB 050509b progenitor similar to long GRBs, i.e. a collapsar origin. Observations of long GRBs at $z < 0.7$ are consistent with all having SN bumps (Zeh, Klose & Hartmann 2003) and all GRBs below 0.4 have had SN features [GRB 980425, $z = 0.0085$, Galama et al. (1998); GRB 031203, $z = 0.1055$, Malesani et al. (2004); GRB 030329, $z = 0.1685$, Hjorth et al. (2003); GRB 011121,

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[2] http://supernova.lbl.gov/~nugent/nugent_templates.html

z = 0.362, Garnavich et al. (2003)] The situation is more unclear regarding X-ray flashes (XRFs); a bright SN was associated with XRF 020903 (z = 0.251) (Soderberg et al. 2005), but no SN (and no optical afterglow) was detected in XRF 040701 (with a probable z = 0.215) down to a limit at least three magnitudes fainter than SN 1998bw (Soderberg et al. 2005).

We now proceed to use our derived limits to constrain the energetic properties of the outflow from GRB 050509b. Bloom et al. (2005) find that both the isotropic equivalent energy output in γ-rays, $E_{\gamma,\rm iso}$, and the afterglow X-ray luminosity, L_X, of GRB 050509b are significantly smaller than those of long GRBs. This is true for any reasonable redshift, and more dramatically so for the redshift of the putative host galaxy ($z = 0.225$). The most straightforward conclusion is that compared to long GRBs, GRB 050509b was an intrinsically less energetic event with relatively little energy [$\lesssim 10^{49}(\Omega/4\pi)$ erg] in highly relativistic ejecta with an initial Lorentz factor $\Gamma_0 \gtrsim 100$ (from $E_{\gamma,\rm iso}$) and with not much more energy in material with $\Gamma_0 \gtrsim 3(E_{51}/n_0)^{1/8}$ (from the *Chandra* upper limit at $t \approx 2.5$ days; (Patel et al. 2005)), where $E_{\rm k,iso} = 10^{51}E_{51}$ erg is the isotropic equivalent energy in the afterglow shock and $n = n_0$ cm^{-3} is the external density.[3] Moreover, the total observed energy from the burst was much smaller than the available energy in a NS-NS or NS-BH merger, or in most other progenitor models suggesting that more energy was released in slower ejecta. The amount of energy in material above a certain initial four-velocity, $E(>\Gamma_0\beta_0)$, is very uncertain theoretically, but may be constrained by our late time upper limit on the optical emission.

There are two ways to produce the most readily detectable emission from the outflow associated with GRB 050509b. It can either originate in the shock created by the outflow as it drives into the ambient medium, similar to both a long GRB afterglow for relativistic ejecta and to a SN remnant for Newtonian ejecta. Or, bright transient emission, dubbed a 'mini SN' (Li & Paczyński 1998; Rosswog & Ramirez-Ruiz 2002), is produced by radioactive elements that are synthesized during the rapid decompression of very dense and neutron rich material that is ejected during a NS-NS or a NS-BH merger (see, e.g., Rosswog et al. 1999). Our upper limit at t = 22.8 days constrains mainly the former mechanism, in particular the amount of energy in ejecta with $\Gamma_0 \gtrsim 1.3(E_{51}/n_0)^{1/8}$, and suggests that the total energy in a relativistic outflow is significantly smaller in GRB 050509b than that in typical long GRBs.[4] Our upper limit at t = 1.85 days pro-

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[3] A higher $E_{\rm k,iso}$ is possible for a very low external density. For $n \sim 10^{-6}$ cm^{-3}, $E_{\rm k,iso} \sim 10^{51}$ erg for $z = 0.225$ and $\sim 10^{52-53}$ erg for $z \approx 3$ (Bloom et al. 2005; Lee, Ramirez-Ruiz & Granot 2005). This would, however, require $E_{\gamma,\rm iso} \ll E_{\rm k,iso}$, i.e., a very inefficient prompt emission (compared to $E_{\gamma,\rm iso} \gtrsim E_{\rm k,iso}$ for long GRBs), and would not naturally reproduce the fact that $L_X/E_{\gamma,\rm iso}$ for GRB 050509b is similar to that for long GRBs.

[4] One possible caveat is the dependence of the afterglow brightness on the density of the burst environment (see Bloom et al. 2005); since the possible counterpart location on G1 spans a large range of densities, we have not folded this dependence in our conclusions.

vides more stringent constraints on the latter mechanism, in which the emission is expected to peak around the optical-UV range within a day or so (up to a few days) with a semi-thermal spectrum (Li & Paczyński 1998). The 'mini SN' emission is mainly concentrated in a very narrow energy range (i.e., the optical) during (and near) the peak; therefore, the X-ray emission could have been easily missed by the *Chandra* observation of GRB 050509b at $t \approx 2.5$ days.

Using the simplified model of Li & Paczyński (1998), the optical flux from a 'mini-SN' associated with GRB 050509b should have been a factor of $\sim 10^3 (f/10^{-3})(M/0.01M_\odot)^{1/2}(3v/c)^{1/2}$ higher than our upper limit at $t = 1.85$ days, where M and v are the mass and velocity of the ejected material, and f is the fraction of its rest energy that goes into radioactive decay. For a kinetic energy of $10^{51}E_{51}$ erg, where $E_{51} = (M/0.01M_\odot)(3v/c)^2 \sim 1$, varying M and v within a reasonable range ($0.003 \lesssim M/M_\odot \lesssim 1$ and $0.03 \lesssim v/c \lesssim 0.5$) would not change the optical luminosity by more than one order of magnitude. A larger uncertainty is the value of f, which reflects the amount of radioactive material synthesized in the accompanying NS-NS wind. From the above simple arguments we derive an approximate upper limit of $f \lesssim 10^{-5}$.

The above arguments suggest that either the intrinsic energy in the outflow from GRB 050509b was $\ll 10^{51}$ erg, or alternatively, and arguably more likely, that it was close to the canonical value of $\sim 10^{51}$ erg but most of this energy was in sub-relativistic ejecta[5] with a very small radioactive component. The latter is very different from long/soft GRBs which typically have $\sim 10^{51}$ erg in highly relativistic ejecta with $\Gamma_0 \gtrsim 100$. We note, however, that we need to obtain more short GRB afterglows to establish whether GRB 050509b is sub-energetic even among short GRBs, and, therefore, apply our conclusions on the bulk of the short/hard GRB class.

Finally, our observations may place constraints on other possible models for short GRB progenitors. For instance, the central object may not become dormant after the gamma-ray burst itself, (e.g., Ramirez-Ruiz 2004). It could be that the accretion-induced collapse of a white dwarf (Tan, Matzner & McKee 2001), or (for some equations of state) the merger of two NS, could give rise to a rapidly-spinning pulsar (Rosswog, Ramirez-Ruiz & Davies 2003), temporarily stabilized by rapid rotation. The afterglow could then, at least in part, be due to a pulsar's continuing power output (Dai & Lu 1998; Rees & Mészáros 2000). It could also be that mergers of unequal mass NS (Shibata & Sekiguchi 2003; Blackman & Yi 1998), or NS with other compact companions (Rosswog et al. 2004; Davies, Levan & King 2005), lead to the delayed formation of a BH. Such events might also lead to repeating episodes of accretion and orbit separation, or to the eventual explosion of a NS which has dropped below the critical mass, all of which would provide a longer time scale, and episodic energy output. The strict optical upper limits derived in this Letter, argue that these scenarios are only feasible if the transport of the energy is in the form of subrelativistic

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[5] Such sub-relativistic velocities could be the result of a significant entrainment of baryons into the outflow.

ejecta with little or almost no radioactivity, or in any other form of delayed energy input such as provided by a pulsar or by later mass ejection by a central source.

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REFERENCES

Alard, C., & Lupton, R. H. 1998, ApJ, 503, 325

Blackman, E. G., & Yi, I. 1998, ApJ, 498, L31

Bloom, J. S., et al. 1999, Nature, 401, 453

Bloom, J. S., et al. 2005, ApJ, submitted (astro-ph/0505480)

Cenko, S. B., Soifer, B. T., Bian, C., Desai, V., Kulkarni, S. R., Berger, E., Dey, A., & Jannuzi, B. T. 2005, GCNC 3391

Dai, Z. G., & Lu, T. 1998, Phys. Rev. Letters,81, 4301

Dado, S., Dar, A., & De Rujula, A. 2005, GCNC 3424

Dar, A., & De Rujula, A. 2004, Phys. Rep., 405, 203

Davies, M. B., Levan, A. J., & King, A. R. 2005, MNRAS, 356, 54

Engelbracht, C.W. & Eisenstein, D.J. 2005, GCNC 3420

Fan, Y. Z., Zhang, B., Kobayashi, S., & Mészáros, P. 2005, ApJ, in press (astro-ph/0410060)

Fynbo, J. P. U., et al. 2004, ApJ, 609, 962

Gal, R. R., de Carvalho, R. R., Lopes, P. A. A., Djorgovski, S. G., Brunner, R. J., Mahabal, A., & Odewahn, S. C. 2003, AJ, 125, 2064

Galama, T. J., et al. 1998, Nature, 395, 670

Garnavich, P. M., et al. 2003, ApJ, 582, 924

Gehrels, N., et al. 2004, ApJ, 611, 1005

Gehrels, N., et al. 2005, Nature, submitted (astro-ph/0505630)

Germany, L. M., Reiss, D. J., Sadler, E. M., Schmidt, B. P., & Stubbs, C. W. 2000, ApJ, 533, 320

Ghirlanda, G., Ghisellini, G., & Celotti, A. 2004, A&A, 422, L55

Gorosabel, J., et al. 2002, A&A, 383, 112

Hjorth, J., et al. 2003, Nature, 423, 847

Hjorth, J., et al. 2005, GCNC 3410

Hurley, K., et al. 2002, ApJ, 567, 447

Kehoe, R., et al. 2001, ApJ, 554, L159

Klotz, A., Boër, M., & Atteia, J.-L. 2003, A&A, 815, 2003

Kouveliotou, C., Meegan, C. A., Fishman, G. J., Bhat, N. P., Briggs, M. S., Koshut, T. M., Paciesas, W. S., & Pendleton, G. N. 1993, ApJ, 413, 110

Lee, W. H., Ramirez-Ruiz, E., & Granot, J. 2005, submitted to ApJL (astro-ph/0506104)

Li, L. X., & Paczyński, B. 1998, ApJ, 507, L59

MacFadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262

Malesani, D., et al. 2004, ApJ, 609, L5

Nugent, P., Kim, A., & Perlmutter, S. 2002, PASP, 114, 803

Patel, S., Kouveliotou, C., Burrows, D. N., Grupe, D., Gehrels, N., Meszaros, P., Zhang, B., & Wijers, R. 2005, GRB Circular Network, 3419, 1

Prochaska, J. X., et al. 2004, ApJ, 611, 200

Richardson, D., Branch, D., Casebeer, D., Millard, J., Thomas, R. C., & Baron, E. 2002, AJ, 123, 745

Richmond, M. W., et al. 1996, AJ, 111, 327

Ramirez-Ruiz, E. 2004, MNRAS, 349, L38

Rees, M. J., & Mészáros, P. 2000, ApJ, 545, L73

Rosswog, S., Liebendörfer, M., Thielemann, F.-K., Davies, M. B., Benz, W., & Piran, T. 1999, A&A, 341, 499

Rosswog, S., & Ramirez-Ruiz, E. 2002, MNRAS, 336, L7

Rosswog, S., Ramirez-Ruiz, E., & Davies, M. B. 2003, MNRAS, 345, 1215

Rosswog, S., Speith, R., & Wynn, G. A. 2004, MNRAS, 351, 1121

Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525

Shibata, M., & Sekiguchi, Y. 2003, Phys. Rev. D, 68, 104020

Soderberg, A. M., et al. 2005, ApJ, submitted (astro-ph/0502553)

Stanek, K. Z., et al. 2003, ApJ, 591, L17

Tan, J. C., Matzner, C. D., & McKee, C. F. 2001, ApJ, 551, 946

Thomsen, B., et al. 2004, A&A, 419, L21

Yamazaki, R., Ioka, K., & Nakamura, T. 2004, ApJ, 607, L103

Zeh, A., Klose, S., & Hartmann, D. H. 2004, ApJ, 609, 952

Zwicky, F., & Herzog, E. 1963, Catalogue of Galaxies and of Clusters of Galaxies, Vol. II, Pasadena: California Institute of Technology

Zhang, W., Woosley, S. E., & MacFadyen, A. I. 2003, ApJ, 586, 356

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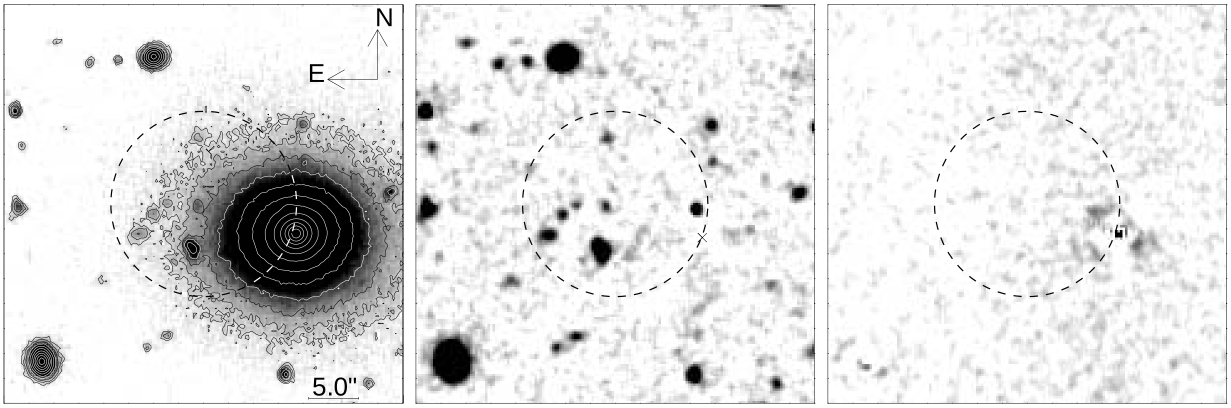

Fig. 1.— *Left*: First epoch V image (3.9 days after burst) showing the putative host E galaxy G1 and several faint galaxies in the XRT error circle. *Middle*: Same, after subtraction of a fit to G1. The cross marks the location of the center of G1. North of it is the new detected source which may be a foreground or background source or a companion to G1. *Right*: Difference between last (22.9 days after burst) and first epoch V images.

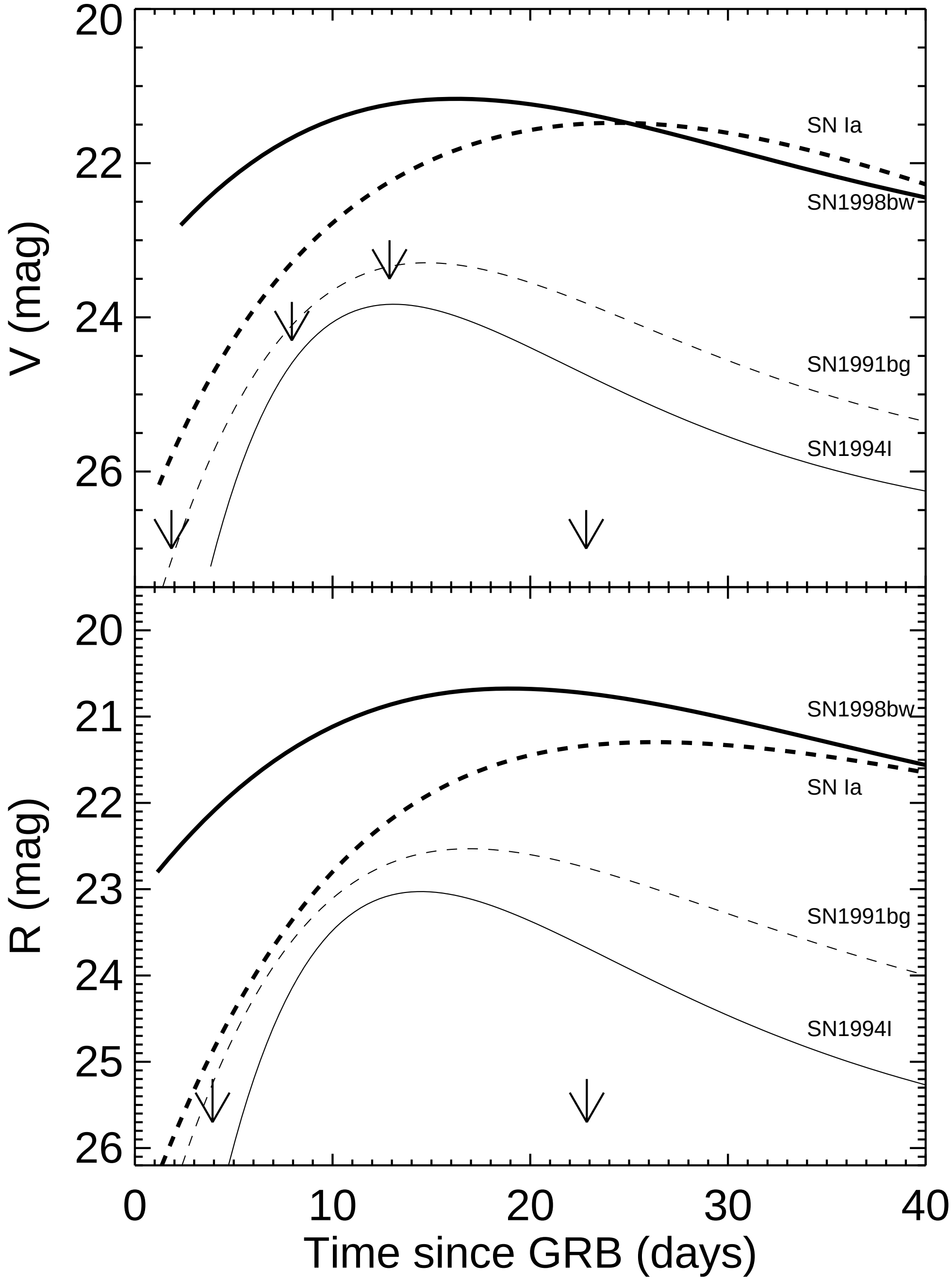

Fig. 2.— The upper limits (*arrows*) on variable sources inside the GRB 050509b XRT error circle at the epochs given in Table 1 compared to the lightcurves of different SNe redshifted to $z = 0.225$. *Solid curves* indicate Type Ic SN, *dashed curves* Type Ia SN. *Thick solid curve*: The hypernova SN 1998bw accompanying the long GRB 980425. *Thin solid curve*: The faint Ic supernova SN 1994I. *Thick dashed curve*: A typical Type Ia SN (stretch = 1). *Thin dashed curve*: A faint Type Ia SN similar to SN 1991bg. A Galactic extinction of $E(B-V) = 0.019$ mag (Schlegel et al. 1998) towards GRB 050509b has been assumed.

Table 1. Log of observations

Date (UT)	Phase (Days past GRB)	Band	Exp. time (s)	Seeing (arcsec)	Lim. mag (mag)
050511.02	1.85	*R*	2700	0.9	26.6
050513.10	3.93	*V*	2700	0.9	27.5
050517.11	7.94	*V*	1800	0.7	25.0
050523.05	12.88	*V*	1800	1.0	24.2
050601.00	22.83	*R*	2700	0.9	26.7
050601.03	22.86	*V*	2700	1.0	27.5

Note. — The quoted 3σ limiting magnitudes are measured in the field in a 2×FWHM aperture. The limiting magnitudes become progressively smaller towards the center of G1.