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# On the nature of the short-duration GRB 050906 ⋆

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## ABSTRACT

We present deep optical and infrared (IR) observations of the short-duration GRB 050906. Although no X-ray or optical/IR afterglow was discovered to deep limits, the error circle of the gamma-ray burst (GRB) (as derived from the *Swift* Burst Alert Telescope, or BAT) is unusual in containing the relatively local starburst galaxy IC328. This makes GRB 050906 a candidate burst from a soft gamma-ray repeater (SGR), similar to the giant flare from SGR 1806−20. The probability of chance alignment of a given BAT position with such a galaxy is small ($\lesssim$1 per cent), although the size of the error circle (2.6 arcmin radius) is such that a higher $z$ origin cannot be ruled out. Indeed, the error circle also includes a moderately rich galaxy cluster at $z = 0.43$, which is a plausible location for the burst given the apparent preference that short-duration GRBs have for regions of high mass density. No residual optical or IR emission has been observed, in the form of either an afterglow or a later time emission from any associated supernova-like event. We discuss the constraints these limits place on the progenitor of GRB 050906 based on the expected optical signatures from both SGRs and merging compact object systems.

**Key words:** gamma-ray: bursts.

## 1 INTRODUCTION

Until recently, the revolution of our knowledge of gamma-ray burst (GRB) sources was limited almost exclusively to those with durations of $t_{90} > 2$ s - so-called long bursts (see e.g. Meszaros 2006 for a review). The discovery of afterglows of the long-duration bursts enabled rapid progress by allowing the identification of redshifts (e.g. Metzger et al. 1997), star-forming host galaxies (e.g. Conselice et al. 2005; Fruchter et al. 2006; Wainwright, Berger & Penprase 2007) and ultimately unambiguous supernova (SN) signatures (e.g. Hjorth et al. 2003) – finally linking long-duration GRBs to the collapse of massive stars.

Afterglows of the short-duration GRBs (S-GRBs) have still only been discovered for relatively few bursts (e.g. Berger et al. 2005; Fox et al. 2005a; Gehrels et al. 2005; Hjorth et al. 2005a; Bloom et al. 2006; Levan & Hjorth 2006; Levan et al. 2006a; Soderberg et al. 2006). None the less, the afterglows (e.g. Fox et al. 2005a; Hjorth et al. 2005a; Burrows et al. 2006; Campana et al. 2006; Grupe et al. 2006) and the host galaxies which they select (e.g. Gal-Yam et al. 2005; Barthelmy et al. 2005; Gorosabel et al. 2006; Prochaska et al. 2006) are apparently different, at least on the average, to those of long-duration GRBs. S-GRBs seem to occur in galaxies of all types including those with older stellar populations, although the statistical significance of such associations is often fairly low (see e.g. Bloom et al. 2007; Levan et al. 2007). S-GRBs are typically located at larger distances from their host galaxy nuclei and are also less luminous and at a lower mean redshift than long-duration bursts (cf. Jakobsson et al. 2006), although at least one short burst (GRB 060121; Levan et al. 2006a; de Ugarte Postigo et al. 2006) apparently originates from significantly higher redshift, and may point to the existence of a larger population of high-redshift S-GRBs. These properties can naturally be explained as being due to the merger of a tight binary consisting of compact objects [neutron stars (NS) or black holes (BH)] following energy and angular momentum dissipation via gravitational radiation (e.g. Rosswog

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& Ramirez-Ruiz 2003; Rosswog, Ramirez-Ruiz & Davies 2003; Davies, Levan & King 2005), although this is by no means the only viable mechanism.

However, while the properties described above are already diverse they may well not represent the whole S-GRB population. The discovery of a massive flare from soft gamma-ray repeater (SGR) 1806−20 (Hurley et al. 2005; Palmer et al. 2005) provided evidence that some fraction of the large sample of S-GRBs found by the burst and transient source experiment (BATSE) could be explained by SGR giant flares in galaxies out to ∼30–40 Mpc and potentially further with *Swift*. Furthermore, a correlation of short bursts detected by BATSE with galaxies within the local Universe (<100 Mpc) reveals that a fraction (between 10 and 25 per cent) of short bursts originate from this nearby large-scale structure (Tanvir et al. 2005). Plausible (but broad) luminosity functions can accommodate both a moderate fraction of bursts in the local Universe and a significant fraction at $z > 0.2$ (Nakar, Gal-Yam & Fox 2006) even if they are from a single class of progenitors. Perhaps rather more likely is that two populations of short bursts are being observed, those from SGR giant flares and those due to other events, most likely NS–NS or NS–BH mergers.

To date, it has not been possible to identify with confidence the individual host galaxies of short bursts which may be due to SGR giant flares, due to the large error regions associated with BATSE bursts and the relative dearth of smaller error boxes from, for example, the interplanetary network (IPN - Hurley et al. 2002). Here, we present optical observations of the field of *Swift*-discovered GRB 050906 (Krimm et al. 2005). The bright, nearby galaxy IC 328 lies within its positional error circle and makes a good case for a S-GRB associated with a SGR giant flare. However, as we show, a higher redshift origin cannot be ruled out, and in particular a bright galaxy cluster at $z = 0.43$ also overlaps the error circle and provides a viable alternative origin for the burst.

## 2 OBSERVATIONS

GRB 050906 was detected with the *Swift* satellite (Gehrels et al. 2004) on 2005 September 6, 10:32 UT (day 6.4389). The onboard reported location was RA = $03^{\rm h}31^{\rm m}13^{\rm s}$, Dec. = $-14^\circ37'30''$, with a positional accuracy of 3 arcmin (Krimm et al. 2005). As the burst was very faint, it was not at first clear if a real GRB had been observed. However, it was pointed out immediately that the error circle of GRB 050906 was unusual in containing a bright, low-redshift galaxy, IC 328 (Levan & Tanvir 2005), which is at a redshift of $z = 0.031$, a distance of only ≈130 Mpc (assuming a standard $\Lambda$ cold dark matter cosmology with $\Omega_{\rm M} = 0.27$, $\Omega_\Lambda = 0.73$, $H_0 = 73{\rm km\ s^{-1}Mpc^{-1}}$).

A prompt slew was performed to the location of GRB 050906 with observations with the X-ray telescope (XRT; Burrows et al. 2005) beginning 79 s after the burst. These observations failed to locate any convincing X-ray afterglow (Pagani, La Parola & Burrows 2005). Subsequently, the Burst Alert Telescope (BAT) localization of GRB 050906 was refined to RA = $03^{\rm h}31^{\rm m}22^{\rm s}$, Dec. = $-14^\circ39'00''$, with a 2.6 arcmin (90 per cent) uncertainty (Parsons et al. 2005). Its $t_{90}$ duration was 128 ms and the total fluence in the 15–150 keV band was very low at $7.0 \pm 3.2 \times 10^{-9}$ erg cm$^{-2}$. No prompt observations were obtained with the UV/Optical telescope (UVOT; Roming et al. 2005) since it was in safe mode at the time of the burst. Full details of the *Swift* observations of GRB 050906 are described in a separate paper (Hurley et al., in preparation), which concludes that the burst would be surprisingly soft if from a SGR giant flare. However, since the properties of giant flares are rather poorly understood, it remains important to look at the other evidence for and against such an explanation in this particular case.

We first observed the error circle of GRB 050906 using the Wide Field Camera (WFCAM) on the United Kingdom Infrared Telescope (UKIRT) beginning at September 6.50 (UT), 1.7 h after the burst (a complete log is shown in Table 1). A *K*-band integration of 40 min was made. A second, similar exposure was obtained the following night (∼26 h after the burst). Deep optical observations were acquired at the European Southern Observatory (ESO) Very Large Telescope (VLT), covering the *VRI* bands (∼1800 s in each band). Three epochs of observations were obtained using the FORS1 and FORS2 imagers at 21 and 140 h and 18 d after the burst. We also obtained deep, late time infrared (IR) observations using VLT/ISAAC (Infrared Spectrometer and Array Camera) in *J*, *H* and *K*. Optical observations were processed through IRAF in the standard fashion. The UKIRT/WFCAM observations were reduced via the ORAC-DR pipeline (Cavanagh et al. 2003) and the VLT/ISAAC observations were processed with ECLIPSE (Devillard 2001).

Cameron & Frail (2005) identified a single radio source within the initial burst error circle (although outside the refined BAT source location), the position of this source is RA = $03^{\rm h}31^{\rm m}11\overset{\rm s}{.}8$, Dec. = $-14^\circ37'18\overset{''}{.}1$. At this location, our images reveal a very red point

**Table 1.** Optical/IR observations of GRB 050906 obtained at UKIRT and the VLT. The date of the start of the observations is shown as is the time since burst and the individual frame limit. The limit for the subtractions was determined via the use of artificial stars. The name in parenthesis is the instrument used to perform the subtraction which yielded this limit.

| Date | $\Delta\ t_{\rm b}$ (d) | Exponent time (s) | Instrument/filter | Limit (frame) | Limit (sub) |
|---|---|---|---|---|---|
| 2005 September 6.502 | 0.06 | 2160 | WFCAM/*K* | 20.2 | 19.5 (WFCAM) |
| 2005 September 7.333 | 0.89 | 1800 | FORS2/*R* | 26.6 | 25.9 (FORS2) |
| 2005 September 7.345 | 0.91 | 1800 | FORS2/*V* | 27.3 | 26.6 (FORS2) |
| 2005 September 7.3670 | 0.93 | 1920 | FORS2/*I* | 25.2 | 24.5 (FORS2) |
| 2005 September 7.510 | 1.07 | 3240 | WFCAM/*K* | 20.4 | 19.5 (WFCAM) |
| 2005 September 12.333 | 5.89 | 1800 | FORS2/*R* | 26.4 | 25.9 (FORS2) |
| 2005 September 12.344 | 5.90 | 1800 | FORS2/*V* | 27.1 | 26.6 (FORS2) |
| 2005 September 12.357 | 5.92 | 1920 | FORS2/*I* | 25.0 | 26.6 (FORS2) |
| 2005 September 25.272 | 18.83 | 1800 | FORS1/*R* | 26.2 | 25.2 (FORS2) |
| 2005 September 25.280 | 18.84 | 1800 | FORS1/*V* | 26.5 | 25.7 (FORS2) |
| 2005 September 25.293 | 18.85 | 1800 | FORS1/*I* | 24.9 | 24.2 (FORS2) |
| 2005 September 29.294 | 22.86 | 320 | ISAAC/*K* | 22.1 | 19.5 (WFCAM) |
| 2005 September 29.340 | 22.90 | 280 | ISAAC/*J* | 23.1 | – |
| 2005 September 29.346 | 22.91 | 208 | ISAAC/*H* | 22.2 | – |

source ($R - K = 5.6$). However, it did not exhibit any variability in the optical or IR and it is likely to be a background galaxy.

Although the prompt XRT X-ray observations failed to locate any strong candidate for the afterglow of the burst, an inspection of the images did produce a possible faint counterpart (Fox et al. 2005b; Butler 2007). However, its association with GRB 050906 and even its reality remain highly uncertain. The refined location of this candidate is RA = $03^{\mathrm{h}}31^{\mathrm{m}}15\overset{\mathrm{s}}{.}28$, Dec. = $-14°36'13\overset{''}{.}1$. We find no evidence either for any variable point sources within this region or for any particular overdensity of galaxies within the large (15.7 arcsec radius) localization.

A detailed inspection of the entire error region within our observations revealed no evidence for new sources by comparison to archival surveys or between our own images taken at different epochs. We estimate the limiting magnitude of each individual frame by examining the signal-to-noise ratios for the photometry of many point sources: the resulting limiting magnitudes are shown in Table 1. In order to search for a variable afterglow (which may be placed on top of a relatively bright host galaxy), we performed point spread function (PSF)-matched image subtractions of the different epochs of imaging using the code of Alard & Lupton (1998). Each epoch of observations was subtracted from each other epoch obtained in the same filter. These subtractions yielded very clean residual images in the cases of using the same telescope and instrument, although larger residuals where observations had to be matched from different telescopes. To estimate the limiting magnitude of any variable sources, we seeded each image with a number of false stars (which were added with the appropriate PSF for the image in which they are seeded) and then repeated the subtractions. The magnitude of sources which can be recovered as residuals at $>5\,\sigma$ in the resulting difference images are also shown in Table 1.

As the error circle of GRB 050906 contains the bright, nearby galaxy IC 328 (and the companion galaxy IC 327 is just outside the error circle), we separately estimate the limiting magnitude for any variable source within the galaxy. These limits are lower than for the field in general since the bright cores of each galaxy leave large residuals in the subtracted images. Any source within 5 arcsec of the centre of either galaxy would have to be $R < 20$ in order to be detected clearly in our residual images. Although this is relatively bright, it should be noted that even a moderately faint SN in IC 328 (e.g. one with $M_V \sim -17$ at maximum), if unextinguished, would reach a peak about 2.5 mag brighter than this.

In addition to IC 328 and 327, visual inspection of our FORS images of GRB 050906 revealed many more distant galaxies, including an overdensity of galaxies in the south-west of the error circle. Although this clustering extended both beyond the error circle and further beyond the field of view of our FORS observations, we estimate that the greatest concentration lies at roughly RA = $03^{\mathrm{h}}31^{\mathrm{m}}17^{\mathrm{s}}$, Dec. = $-14°41'25''$, although the distribution of galaxies is not uniform and exhibits at least two (possibly more) regions of overdensity (see Fig. 2).

We obtained spectroscopy of two galaxies from this concentration using Gemini South and Gemini Multi–Object Spectrograph (GMOS) on 2006 January 26, with the G300V grating. The galaxies in question are marked in Figs 1 and 2. Spectra were reduced in the standard fashion using the specific GMOS scripts within IRAF. Inspection of these spectra reveals strong absorption features which we attribute to Ca H & K, and H$\delta$ at a redshift of $z = 0.43$.

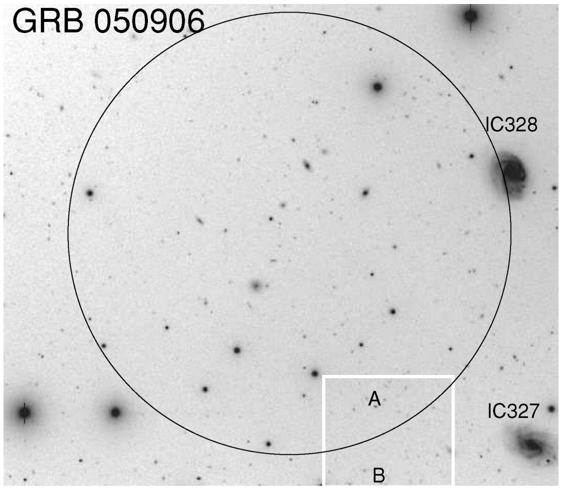

**Figure 1.** Finding chart for GRB 050906. North is up and east is to the left. The GRB error circle of 5.2 arcmin diameter is shown. As can be seen, the bright, low-redshift galaxy IC 328 lies on the edge of this error circle, which would be an unlikely chance coincidence if it is not associated with the GRB. However, there are many other more distant galaxies clearly seen in the field, including a galaxy cluster which, as discussed in the text, is also a viable location of the GRB. Fig. 2 shows an enlarged region about this cluster and the area shown is marked by the white box.

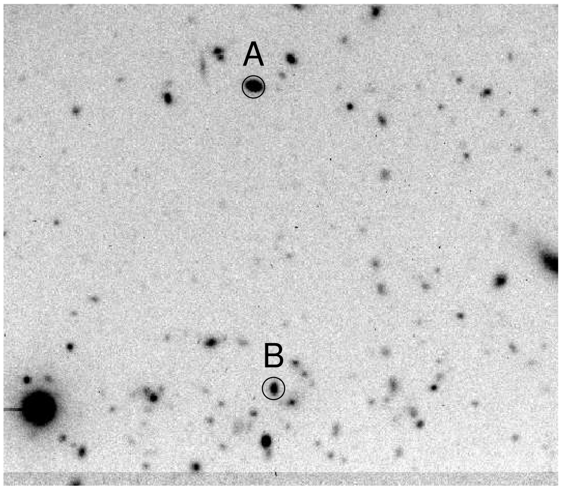

**Figure 2.** A $z = 0.43$ cluster lying within the error circle of GRB 050906. The two galaxies marked A and B have spectroscopic redshifts, while the other galaxies exhibit similar colours and are likely to lie within the same cluster.

## 3 THE PROPERTIES OF IC 328

IC 328 is a bright $K = 11.4$ galaxy and its colours, and somewhat disturbed morphology, are consistent with an actively star-forming, late-type galaxy. Its observed $B$-band magnitude ($B_0 = 14.9, M_B = -20.7$) is approximately $L^*$ and its $R - K$ colour of $\approx 2.3$ is very blue, also indicative of ongoing star formation. IC 328 was detected by *IRAS* in all four bands (10, 25, 60, 100 μm). Converting from the observed 60 μm flux to a star formation rate (SFR) assuming a relation of SFR = $5.5(L_{60}/5.1 \times 10^{30}\,\mathrm{erg\,s^{-1}\,Hz^{-1}})$ (Kennicutt 1998) results in a SFR for IC 328 of $\sim 17\,\mathrm{M_{\odot}\,yr^{-1}}$. Fig. 3 shows the spectral energy distribution (SED) of IC 328 (see also Table 2) overlaid with several comparison spectra (standard Sc, M51 and M82). An

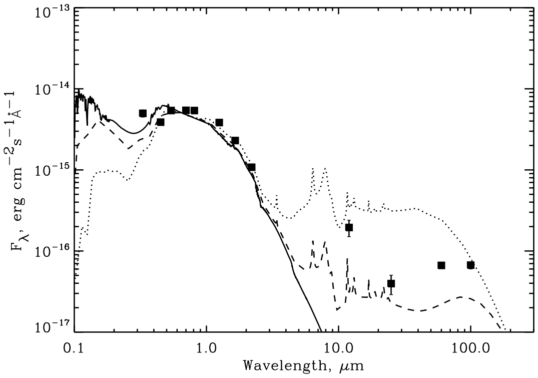

**Figure 3.** The spectral energy distribution of IC 328. Overlaid with template spectra for an Sc galaxy (solid line), M51 (dashed line) and M82 (dotted line). The spectra have been normalized to the $R$-band flux. Extrapolating from the M51 template, we thus obtain a SFR of $3\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$, somewhat lower than that inferred from the 60-μm flux.

alternative means of estimating the SFRs is to scale these template spectra such that they provide a reasonable fit to the observed spectral energy distribution of IC 328. Doing this with M51 yields a SFR of $\sim 3\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$, significantly lower than via the 60 $\mu$m flux, but consistent with the idea that much of the star formation in IC 328 is dust obscured, leading to the high far-IR fluxes.

SGRs are commonly thought to be formed via the core-collapse of massive stars and thus would trace the SFR of a given galaxy, although they may also be produced via accretion-induced collapse (AIC) of merging white dwarfs (WDs) (Usov 1992; Levan et al. 2006b) and SGRs formed via this channel should trace the stellar mass density. The IR luminosity of IC 328 implies that it is moderately massive: using the stellar mass estimation scheme of Mannucci et al. (2005) yields $M \sim 10^{11}\,\mathrm{M}_{\odot}$. Thus, IC 328 appears in terms of mass to be similar to the Milky Way (MW), and in terms of star formation rather more active than the MW by factors of several, and hence can be expected to harbour at least a similar number of SGRs.

If originating from IC 328, the isotropic equivalent energy of GRB 050906 would be $E_{\mathrm{iso}} \sim 1.5 \times 10^{46}$ erg in the 15–150 keV range. This compares to a total energy release (>30 keV) of $E_{\mathrm{iso}} \sim 4 \times 10^{46}$ erg for the giant flare from SGR 1806−20 (Hurley et al. 2005).

Galaxies such as IC 328 are rare in GRB error circles only a few arcmin in diameter. To estimate the probability of a chance alignment, we simulated a large set of GRB positions placed randomly on the sky and subsequently searched for galaxies within 3 arcmin of these positions (our galaxy catalogue was the complete *IRAS* Point Source Catalog of Redshifts (PSC*z*) catalogue, which contains IC 328 and is thus a good catalogue to search for similar galaxies). In a total of 50 000 random bursts, only 135 matches were found, allowing for the 15 per cent avoidance of the Galactic plane in the PSC*z* survey; this implies a probability of selecting IR-bright galaxies such as IC 328 of only 0.003. There are, of course, alternative ways in which this probability analysis could have been performed, for instance using optically selected galaxy catalogues. However, we feel that our approach is suitably conservative (e.g. we might have cut the PSC*z* sample to galaxies as bright as IC 328 or brighter), and therefore gives a useful indication of the low likelihood of a chance coincidence.

We emphasize that this probability should not simply be regarded as an a posteriori calculation. Tanvir et al. (2005) had already predicted that a non-negligible proportion of S-GRB should be associated with low-redshift galaxies, so it is statistically reasonable, therefore, to specifically test the null hypothesis that there is no such association. At the time of writing, roughly a dozen short bursts have been observed by *Swift*, and a similar number previously well-localized by IPN and *HETE-2/BeppoSAX* (although those detected by the IPN have a significantly different selection function so comparing their properties with *HETE-2/SXC* and *Swift* bursts is non-trivial). In any event, based on our analysis above, we can say with some confidence that the probability of a *chance* occurrence of such a nearby and bright galaxy as IC 328 in *one or more* of the *HETE-2/SXC* and *Swift*/BAT burst error regions is less than 10 per cent.

Further, although none of the other short bursts detected by *Swift* has plausible local hosts, the IPN has delivered locations for two S-GRBs that may originate in very local galaxies. First, GRB 051103 has an error box which overlaps the outskirts of both M81 and M82 (Ofek et al. 2006; Fredericks et al. 2007), while the recent GRB 070201 has an error box which intersects the spiral arms of M31 (Golenetskii et al. 2007; Hurley et al. 2007). These locations lend support to the results of Tanvir et al. (2005) that a fraction of short bursts should originate in the local Universe and give further credence to the suggestion that IC 328 is the host galaxy of GRB 050906.

**Table 2.** Optical/IR observations of IC 328 and 327 obtained from the literature as cited and via our VLT observations. The optical/near-IR photometry has been corrected for foreground extinction following Schlegel, Finkbeiner & Davis (1998).

| Filter | IC 328 | IC 327 | References |
|---|---|---|---|
| $U$ | 14.3 | – | Coziol et al. (1994) |
| $B$ | 14.9 | 15.15 ± 0.12 | Coziol et al. (1994) |
| $V$ | 14.28 ± 0.02 | 14.93 ± 0.02 | This work |
| $R$ | 13.60 ± 0.02 | 14.45 ± 0.02 | This work |
| $I$ | 13.05 ± 0.02 | 13.95 ± 0.02 | This work |
| $J$ | 12.48 ± 0.02 | 12.90 ± 0.05 | 2MASS |
| $H$ | 11.64 ± 0.05 | 12.37 ± 0.08 | 2MASS |
| $K$ | 11.35 ± 0.06 | 12.13 ± 0.10 | 2MASS |
| *IRAS* 12 μm | $(9.36 \pm 2.15) \times 10^{-2}$ Jy | $<9.32 \times 10^{-2}$ Jy | Moshir et al. (1990) |
| *IRAS* 25 μm | $(8.26 \pm 2.25) \times 10^{-2}$ Jy | $<7.70 \times 10^{-2}$ Jy | Moshir et al. (1990) |
| *IRAS* 60 μm | 0.80 ± 0.05 Jy | 0.21 ± 0.04 Jy | Moshir et al. (1990) |
| *IRAS* 100 μm | 2.23 ± 0.29 Jy | < 2.13 Jy | Moshir et al. (1990) |
| 1.4 GHz | – | 2.7 ± 0.5 mJy | Condon et al. (1998) |

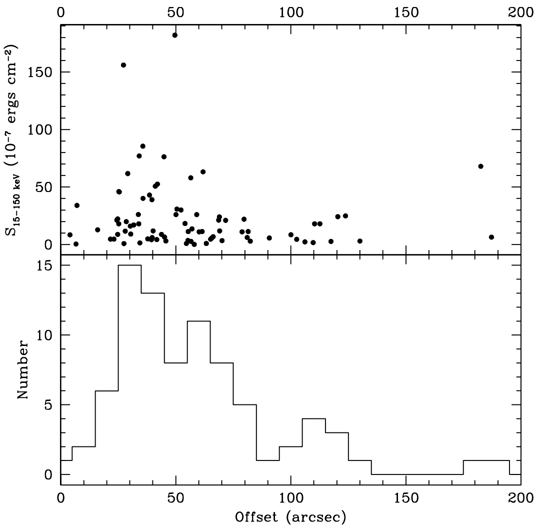

**Figure 4.** The offset distribution between the refined BAT localizations and the positions of the X-ray afterglows of GRBs detected by *Swift*. GRBs have been plotted for the period of one full year of *Swift* operations, from 2005 April 1 to 2006 March 30 (94 bursts with X-ray afterglow locations). As can be seen, the majority of *Swift* bursts lie relatively close to the refined BAT position. Formally, 67 per cent lie within 62 arcsec and 90 per cent lie within 109 arcsec. The probability of locating an afterglow greater than 160 arcsec from the burst position is ~2 per cent and is dominated by the two outliers, GRB 060109 and GRB 060218. There is perhaps a slight trend towards larger offsets for fainter bursts on the average.

However, it is also important to ask what is the probability of finding IC 328 at the position we do in the error circle if it is truly associated with the burst. Formally, only a small fraction of IC 328 lies within the refined BAT error circle, which, although nominally 90 per cent confidence, are typically conservative (Fenimore, private communication), although this may not be the case for the very short and faint GRB 050906. To gauge the number of bursts which we might expect to lie >2.5 arcmin from the BAT localization, we have plotted in Fig. 4 the offset distribution between XRT and BAT positions for all bursts exhibiting afterglows to the XRT in the first year of full *Swift* operations. This shows that, in fact, 90 per cent of the bursts occur within 110 arcsec of the BAT localization, and thus, even faint bursts like GRB 050906 should rarely (~2 per cent of bursts) be at the radial separation of IC 328 from the centre of the BAT error circle. Hence, while the association of GRB 050906 with IC 328 remains plausible, and would have been identified as the host galaxy by various approaches (e.g. that of Gal-Yam et al. 2005), the location at the edge of the error circle does somewhat weaken the case for an association.

Of course, were GRB 050906 due to a low-luminosity NS–NS merger event within IC 328 (or even IC 327) then it may be expected to be at a large distance from its parent galaxy either because it took place in the halo (e.g. a globular cluster) or having been ejected outside the main body of the galaxy by a natal SN kick. A kick of 30 kpc (e.g. similar to that inferred for GRB 050509B) would have led to an offset of ~1 arcmin and could place GRB 050906 relatively closer to the BAT localization. Additionally, the error circle contains a number of fainter (but still moderately bright) galaxies whose colours and physical sizes could well associate them with a group containing IC 328 and 327. Several of these galaxies lie relatively close to the centre of the BAT error box.

## 4 OTHER GALAXIES WITHIN THE ERROR CIRCLE

In addition to IC328 and the possibly associated galaxies described above, there are many more fainter galaxies which probably lie at a range of higher redshifts. The most notable structure is a relatively rich galaxy cluster which overlaps the southern part of the error circle, which, as discussed in Section 2, is at $z = 0.43$. Some previously well-localized short bursts have been found to lie in regions of high mass density (e.g. in elliptical galaxies or cluster environments - Gehrels et al. 2005; Pedersen et al. 2005; Bloom et al. 2006), although the faint, and likely high redshift, host galaxies to GRB 060121 (Levan et al. 2006a; de Ugarte Postigo et al. 2006) and GRB 060313 (Hjorth et al., in preparation) indicate this is not necessarily the case and that a significant fraction of S-GRBs may originate at higher redshift (Berger et al. 2007b). Thus, it is certainly plausible that GRB 050906 originated in this cluster. Its duration of 128 ms is comparable to that of GRB 050509B and, at $z = 0.43$, its inferred isotropic energy release would be $E_{\mathrm{iso}} = (3.2 \pm 1.4) \times 10^{48}$ erg, would also place it along with GRB 050509B ($t_{90} = 40$ ms, $E_{\mathrm{iso}} = 1 \times 10^{48}$ erg; Gehrels et al. 2005) as the intrinsically faintest of the cosmological S-GRBs seen to date.

## 5 IMPLICATIONS FOR PROGENITOR MODELS

The leading contenders for the progenitors of S-GRBs are those which are the result of compact binary mergers (NS–NS, NS–BH and possibly WD–BH – see e.g. Lee & Ramirez-Ruiz, for a review) and those resulting from giant flares from SGRs. Observations of S-GRBs detected by *Swift* provide some support for the former model, while the giant flare from SGR 1806−20 (Hurley et al. 2005; Palmer et al. 2005) provided renewed impetus to investigate SGRs as candidate progenitors. In particular, these may be responsible for the fraction of S-GRBs in the local Universe reported by Tanvir et al. (2005), and for the two subsequently detected IPN bursts which may have originated from M81/82 and M31. The most intense spike of the SGR 1806−20 event would have been detected by BATSE as a short-hard GRB had it occurred out to about 30–40 Mpc (Hurley et al. 2005; Palmer et al. 2005), and it would be positively surprising if some proportion of BATSE S-GRBs were not due to such events occurring in nearby galaxies. Most estimates of the volume average SFR in the local Universe put it at about $0.02\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}\mathrm{Mpc}^{-3}$ (e.g. Iglesias-Páramo et al. 2006). So, in a sphere of radius 100 Mpc we would expect to find a total rate of star formation roughly 20 000 times the current rate in the MW. SGRs are thought to be young (and short lived), highly magnetized NS, and so their number within a galaxy may reflect its SFR (but see Levan et al. 2006b for a possible route to creating magnetars in old stellar populations via WD–WD mergers). Thus, even if a SGR 1806−20-like event were only to occur in the MW on average once every two millenia, ~10 per year should occur within this volume. Of course, the SGR 1806−20 flare itself might not have been quite luminous enough to have been detected to 100 Mpc, but equally, it is unlikely that this event was at the very peak of the luminosity function, and the rate of lower luminosity flares may be greater.

We must bear in mind that the observed afterglows of many S-GRBs have been relatively faint in comparison to typical long bursts (Berger et al. 2005; Fox et al. 2005a; Hjorth et al. 2005a; Levan et al. 2006a; Soderberg et al. 2006). Although some are relatively bright, especially in X-rays (e.g. 050724, Barthelmy et al. 2005; Campana et al. 2006; GRB 051121, Burrows et al. 2006 and GRB 060313, Roming et al. 2006), a fraction are very faint or undetected both in the optical (Hjorth et al. 2005b; Castro-Tirado et al. 2005; Bloom et al. 2006) or in X-ray (e.g. Mineo et al. 2005; La Parola et al. 2006; Page et al. 2006). Similarly, SGRs appear to produce little optical/IR emission during their giant flares, although constraints are not strong. This is partly due to the Galactic SGRs being in the plane of the MW and hence along dusty lines of sight, which would be less of an issue for an observer oriented more face-on to the Galactic plane.

SGR giant flares may produce optical emission, and indeed mini-fireball models can accurately represent the radio and X-ray emission following the giant flare of SGR 1806−20. Being close to the galactic plane provides a considerable challenge to optical observations, although a candidate faint counterpart to SGR 1806−20 has been identified from near-IR *K*-band observations (Israel et al. 2005; Kosugi, Ogasawara & Terada 2005). However, the extrapolation of the expected SGR X-ray flux into the optical waveband and the subsequent extrapolation out to the distance of IC 328 falls below the detection limits of our observations, especially given (i) SGRs are likely to be located close to the nucleus of the galaxy where our limits are least constraining, and (ii) we infer a high proportion of star formation in IC 328 is dust-obscured.

The SGR scenario is not the only possibility for this burst, since it is plausible that another progenitor system created the GRB either in IC 328 or in a more distant galaxy. Indeed, the error box of GRB 050906 also appears to contain a high-redshift cluster, an environment in which several S-GRBs have been found (e.g. Gal-Yam et al. 2005; Pedersen et al. 2005; Berger et al. 2007a). We thus cannot rule out a burst originating from a galaxy associated with this cluster and consider below the implications for short bursts located in either IC 328 or the higher $z$ cluster.

The principle alternative model is that of NS–NS mergers. These might also be expected to result in bright though relatively short-lived optical emission due to the production of heavy elements during the mergers (e.g. Li & Paczyński 1998) – so-called mini-SN or macro-novae (MNe). These transients can reach absolute magnitudes comparable to those of supernovae, although typically last for a much shorter duration, peaking only a day or so after the merger (although the precise behaviour depends on the nuclear yields in the merger itself which are only poorly understood; but see Rosswog et al. 1999). In Fig. 5, we show the limits on any residual emission within the GRB 050906 error circle. We also overplot the SNIc SN 2002ap at the distance of IC 328 ($z = 0.03$).

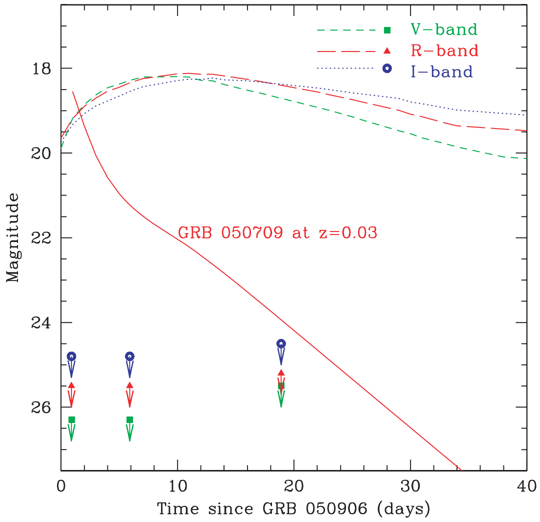

**Figure 5.** SN limits in the field of GRB 050906 assuming that it lies at $z = 0.03$. The light curves shown are those of SN 2002ap (Foley et al. 2003) – which was a Type Ic SN with a peak $M_V = -17$. Also shown is the extrapolated light curve of GRB 050709 as it would appear at $z = 0.03$. As can be seen, the observed limits lie significantly below these extrapolations.

We do not overplot the predicted magnitudes for any MNe emission since the behaviour of such transients is only known from theory as none has been directly observed. However, canonical parameters thought to be associated with NS–NS mergers (e.g. Kulkarni 2005) would predict that they would reach peak fluxes of $\sim 0.1$ μJy at $z = 0.2$, or several μJy ($R \sim 22$) when extrapolated to the distance of IC 328. The models also predict that they will reach this maximum on a time-scale of hours to days past the explosion, and can therefore be searched for in our deep optical imaging 1, 6 and 19 d post burst. Although previous S-GRBs have not shown any sign of MNe emission (e.g. Fox et al. 2005a; Hjorth et al. 2005a,b; Bloom et al. 2006), these bursts lay at distances more than an order of magnitude greater than IC 328, and any SN-like event occurring within them would thus need to be significantly (∼5 mag) brighter. Furthermore, as NS–NS systems have long lifetimes and significant natal kicks it is unlikely that a NS–NS system would be buried within the disc of IC 328. Therefore, while the properties of associated MNe events remain highly uncertain, given the current predications of their brightness it would be somewhat unexpected that our deep observations would not uncover any indication of them should GRB 050906 originate at the distance of IC 328. This lack of emission can be remedied with NS–NS mergers if (i) the NS–NS merger expelled very little mass or radioactive material or (ii) the true distance to GRB 050906 is significantly beyond IC 328 (e.g. in the cluster at $z = 0.43$).

## 6 CONCLUSIONS

We have presented deep optical and IR observations of GRB 050906, the fourth S-GRB to be localized by *Swift* to a few arcmin error. Although these observations fail to locate any optical or IR afterglow (or associated SN event) to deep limits, they do provide information on the possible environment of the burst. Previous short bursts have been shown to be associated with a range of host galaxy types, including those with older stellar populations, over a wide span in redshift (e.g. Nakar et al. 2006; Berger et al. 2007b). There are indeed many distant galaxies within the GRB 050906 positional error circle, including parts of a bright galaxy cluster at $z = 0.43$. It is quite plausible that GRB 050906 originates in a galaxy associated with that cluster and is a short burst comparable to those which have already been localized by *Swift*.

However, GRB 050906 is unusual in that it also contains within its error circle a luminous local galaxy, IC 328, with a high SFR. The likelihood of such a galaxy appearing by chance in a *Swift*/BAT error circle is less than 1 per cent. In addition, this galaxy is likely to host a large number of SGRs since it is both massive and actively star forming, and thus GRB 050906 may be the first example of a well-localized S-GRB due to a SGR giant flare. The inferred isotropic energy release at the distance of IC 328 is very comparable to that of the initial spike in the recent SGR 1806−20 giant flare, although GRB 050906 has a distinctly softer gamma-ray spectrum (Hurley et al., in preparation). The location of IC 328 at the edge of the BAT error circle weakens but does not rule out the case for such an association. Indeed, we note that giant flares like that of SGR 1806−20 would have to be remarkably rare events in order for them not to be present in reasonable numbers in the BATSE short-burst catalogue, and therefore further examples are to be expected during the lifetime of *Swift*.

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