Radio limits on off-axis GRB afterglows and VLBI observations of SN 2003gk

M. F. Bietenholz\textsuperscript{1,2}, F. De Colle\textsuperscript{3}, J. Granot\textsuperscript{4}, N. Bartel\textsuperscript{2} and A. M. Soderberg\textsuperscript{5}

\textsuperscript{1}Hartebeesthoek Radio Observatory, PO Box 443, Krugersdorp, 1740, South Africa
\textsuperscript{2}Dept. of Physics and Astronomy, York University, Toronto, M3J 1P3, Ontario, Canada
\textsuperscript{3}Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, A. P. 70-543 04510 D. F., Mexico
\textsuperscript{4}Department of Natural Sciences, The Open University of Israel, 1 University Road, P.O. Box 808, Ra’anana 43537, Israel
\textsuperscript{5}Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, US

\textsuperscript{6}February 2014; Accepted to MNRAS

ABSTRACT

We report on a VLA survey for late-time radio emission from 59 supernovae (SNe) of Type I b/c, which have been associated with long-duration gamma-ray bursts (GRBs). An “off-axis” GRB burst (i.e. whose relativistic jet points away from us) is expected to have late-time radio emission even in the absence of significant prompt gamma-ray emission. From our sample, we detected only SN 2003gk with an 8.4-GHz flux density of $2260 \pm 130 \mu$Jy. Our subsequent VLBI observations of SN 2003gk, at an age of $\sim 8$ yr, allowed us to determine its radius to be $(2.4 \pm 0.4) \times 10^{17}$ cm, or $94 \pm 15$ light days. This radius rules out relativistic expansion as expected for an off-axis GRB jet, and instead suggests an expansion speed of $\sim 10 \, 000 \, \text{km s}^{-1}$ typical for non-relativistic core-collapse supernovae. We attribute the late-onset radio emission to interaction of the ejecta with a dense shell caused by episodic mass-loss from the progenitor.

In addition, we present new calculations for the expected radio light curves from GRB jets at various angles to the line of sight, and compare these to our observed limits on the flux densities of the remainder of our SN sample. From this comparison we can say that only a fraction of broadlined Type I b/c SNe have a radio-bright jet similar to those seen for GRB afterglows at cosmological distances. However, we also find that for a reasonable range of parameters, as might be representative of the actual population of GRB events rather than the detected bright ones, the radio emission from the GRB jets can be quite faint, and that at present, radio observations do not place strong constraints on off-axis GRB jets.

Key words: Supernovae: individual (SN2003gk) — radio continuum: general

1 INTRODUCTION

Long-duration gamma-ray bursts (GRBs) are thought to involve the highly directed relativistic ejection of material from a collapsing massive star, in other words the formation of relativistic jets. The observed gamma-ray emission is produced within the outflow, outside of the progenitor star but before there is significant deceleration by the surrounding medium. The ejected material interacts with the circumstellar material (CSM) and strong shocks are produced. These shocks amplify the magnetic field and accelerate particles to relativistic energies, the combination of which results in synchrotron emission. For reviews of GRBs see for example Piran (2004), Mészáros (2006), Granot (2007) and Gehrels, Ramirez-Ruiz & Fox (2009).

A GRB is observed when such a jet is directed close to the line of sight, and strong Doppler boosting is responsible for the characteristic bright gamma-ray emission. It follows from this model, however, that the majority of GRB events have jets which are not oriented near the line of sight, and therefore go undetected (Rhoads 1997; Granot et al. 2002; Nakar, Piran & Granot 2002), with Frail et al. (2001) estimating that $>99\%$ of GRB events go undetected.

However, on the basis of several nearby ($z < 0.3$) long-duration GRBs it has been established that they are associated with supernovae (SNe) of Type Ib/c, which are ones from a progenitor star that has lost much of its envelope prior to the explosion (e.g. Galama et al. 1998; Stanek et al. 2003; Malesani et al. 2004; Fian et al. 2006; Cobb et al. 2010; Starling et al. 2011; Xu et al. 2013). In addition, there is indirect evidence for this association, such as large ongoing specific star formation rates at the location of the GRBs in their host galaxies, or late-time red bumps in their afterglow lightcurves (see, e.g. Woosley & Bloom 2006, and references therein). These events therefore feature both highly colli-
mated relativistic jets giving rise to the GRB and an associated more isotropic and non-relativistic SN explosion. This duality underlies the popular “collapsar” model (Woosley 1993; MacFadyen, Woosley & Heger 2001) in which a central engine (accreting, rapidly spinning compact object) drives the relativistic jets while the spherical SN explosion is powered by neutrinos.

GRB events, in addition to the gamma-ray emission, also produce longer-lived emission at lower frequencies, called the afterglow. In particular, afterglows are often detected in radio (see, e.g., van Paradijs, Kouveliotou & Wijers 2000; Zhang 2007). As the GRB decelerates to mildly or sub-relativistic speeds, it produces strong, nearly isotropized, radio emission. The radio emission is much less strongly beamed than the gamma-ray emission, and so in the radio “off-axis” events are not significantly more difficult to detect than on-axis ones at sufficiently late times. Indeed, it has been shown that the radio is probably the best wavelength range for detecting such off-axis events (e.g. Paczynski 2001; Granot & Loeb 2003).

Models of off-axis GRB events developed so far have typically shown that, for angles to the line of sight of 30° to 90°, the radio brightness peaks \( t \) to \( \sim 2 \) years after the explosion (van Eerten, Zhang & MacFadyen 2010; Granot & Loeb 2003). Future large-area surveys with instruments such as ASKAP, LOFAR, MeerKAT, and of course SKA, will likely detect such off-axis events in blind surveys. At present, however, detection in a blind survey is challenging, and radio observations are mostly restricted to follow-up observations of events previously detected in other wavelengths (see Chandra & Frail 2012, and references therein).

Type I b/c SNe provide the ideal locations to search for off-axis GRB events. Since non-relativistic SNe can also produce radio emission, some means of distinguishing the radio emission from putative off-axis jet from that of the normal SN is needed. In the models available at present, the timescales of the two processes are notably different and could therefore provide the necessary discriminant. In particular, the models suggested that radio emission from an off-axis event had a relatively long interval between the explosion and the time of maximum radio emission, so that for angles to the line of sight of 30° to 90°, the peak radio brightness typically occurs \( \sim 1 \) to \( \sim 2 \) years after the explosion (van Eerten, Zhang & MacFadyen 2010; Granot & Loeb 2003). The radio emission from normal Type I b/c SNe, on the other hand, has short timescales, with rise-times at 8.4 GHz of typically a few weeks to months after the explosion, followed by a relatively rapid decay with flux density, \( S \) approximately \( \propto t^{-1.5} \) (Chevalier & Fransson 2006; Weiler et al. 2002). Off-axis GRB events are also distinguished by having high peak spectral luminosities, generally \( > 10^{38} \) erg s\(^{-1}\) Hz\(^{-1}\) (8.4 GHz), while those of normal Type I b/c SNe are mostly \( < 10^{38} \) erg s\(^{-1}\) Hz\(^{-1}\), although some very radio bright normal SNe are known (see, e.g. Soderberg 2007), such as SN 2003L (Soderberg et al. 2005).

The models therefore suggested that late-onset and luminous radio emission from a Type I b/c SN could be used as a signpost of an off-axis GRB event. Soderberg et al. (2006b) carried out a search for such events, and observed 68 Type I b/c SNe in the radio at late times. They did not detect any radio emission and concluded that only a fraction of \(< 10%\) of all Type I b/c SN are associated with a bright GRB jet regardless of orientation. They could also rule out, at the 84% confidence level, the hypothesis that all of the subset of Type I b/c SNe which had broad absorption lines and are therefore classified as “broad-lined” (sometimes also termed “hypernovae”) such as SN 2003jd or SN 2002ap, are associated with GRB events.

Should late-onset radio emission be detected from a Type I b/c, and important diagnostic would be the size of the radio emitting region. If it is indeed due to a relativistic jet, sizes on the order of one light-year are expected. Non-relativistic SNe, however, expand much more slowly, typically with initial speeds of \( 0.1 \) c and average speeds on the order of \( 10 \) 000 km s\(^{-1}\) over periods of \( > 1 \) yr, and would therefore be an order of magnitude smaller.

Indeed there have been several Type I b/c SNe suspected of possibly harbouring an off-axis GRB where subsequent VLBI observations showed that there was no relativistic expansion (see Bietenholz 2014, for a recent review of VLBI observations of Type I b/c SNe). SN 2001em showed late-onset radio emission (Granot & Ramirez-Ruiz 2004; Bietenholz & Bartel 2005, 2007; Schinzel et al. 2009). The late turn-on radio emission from SN 2001em was subsequently interpreted as radio emission produced by the interaction of normal (non-relativistic) Type I b/c ejecta with a massive and dense circumstellar shell located at some distance from the progenitor, produced by mass-loss from the latter, perhaps due to an eruptive event like those of luminous blue variables (Chugai & Chevalier 2006; Chevalier 2007). SN 2007bg and the supernova PTF 11gc also showed late-onset radio-emission (Salas et al. 2013; Corsi et al. 2014) that is also attributed to the interaction of a non-relativistically expanding shock with dense shells of circumstellar material produced by episodic mass loss of the progenitor. In another case, SN 2007gr, it was initially claimed that the VLBI observations implied relativistic expansion (Paragi et al. 2010), however, Soderberg et al. (2010a) subsequently suggested that all the observations could be explained by an ordinary, non-relativistically expanding SN.

In a third nearby Type I b/c SN, SN 2009bb, the high radio luminosity also suggested relativistic ejection (Soderberg et al. 2010b). In this case the VLBI observations were consistent with, but did not demand, mildly relativistic expansion (Bietenholz et al. 2010b).

The radio lightcurve of a non-relativistic SN generally has a steep rise, as the radio emission is initially absorbed by either synchrotron self-absorption or, less commonly for Type I b/c SNe, by free-free absorption due to an optically thick CSM (see, e.g. Chevalier 1998). Once the SN has become optically thin at the frequency of interest, the lightcurve generally decays. The canonical model of Chevalier (1982), which assumes power-law radial density profiles for both the CSM and the ejecta, produces a power-law decay in the lightcurve after the peak. The interval between the explosion and the peak radio brightness is a function of the observing frequency, generally being longer at lower frequencies. It should however, be noted, that significant departures from a strictly power-law decline in the radio emission are relatively common (e.g. SN 2009bb Bietenholz et al. 2010b, SN 1996Cr Meunier et al. 2013, SN 1986J, Bietenholz, Bartel & Rupen 2002, 2010, SN 1979C Bartel & Bietenholz 2008).

As there are as yet no confirmed examples of off-axis GRB jets without a detected gamma-ray signature it would
be very important to detect one, or even in the absence of a detection to set limits on the fraction of Type I b/c SNe which are associated with a relativistic ejection. Earlier work by Soderberg et al. (2006b); Soderberg, Frail & Wieringa (2004) and Gal-Yam et al. (2006) showed that at most a small fraction of Type I b/c can be associated with bright jets typical of detected cosmological GRBs. Nonetheless, if the current paradigm of GRBs involving highly directed ejection is correct, then for every observed GRB there must be many as yet unobserved off-axis events. Searching for late-time radio emission seems a relatively promising way to detect such an event, despite the knowledge that many Type I b/c SNe will have to be searched to obtain one detection.

We therefore undertook a radio survey of Type I b/c SNe with declinations $\sim -30^\circ$ and with ages between 1 and 8 yrs to look for late-time radio emission using the NRAO Very Large Array (VLA). In Section 2 we describe this survey and give the results. One object, SN 2003gk, was detected, and in Section 3 give our followup VLA and VLBI observations of SN 2003gk.

In Section 4 we calculate new modelled radio lightcurves for off-axis GRB jets, and compare them to our observations in Section 5. We discuss the implications of our results in Section 6, and summarize our conclusions in Section 7.

## 2 Survey for late-time radio emission from type I b/c supernovae

### 2.1 VLA survey observations

We use the VLA to survey a sample of 59 Type I b/c SNe with declinations $\sim -30^\circ$ and with ages between 1 and 8 yrs, for late-time radio emission. We chose ordinary Type I b/c SNe only at distances $\lesssim 80$ Mpc, but we also observed several Type I b/c SNe of the “broadlined” subtype which is most reliably associated with GRBs out to slightly larger distances up to 120 Mpc. Our sample is not intended to be complete, merely representative.

We observed in two sessions of 4 hours each, on 2009 May 28 and May 29 (observing code AB1327). The array was in the CnB transitional configuration, and we observed with a total bandwidth of 100 MHz around a central frequency of 8.435 GHz. The data reduction was carried out in the standard way, using 3C 48 and 3C 286 as flux density calibrators on the two days respectively (using the VLA 1999.2 flux density scale). Each SN was observed for $\sim 7.3$ min, with phase calibration derived from bracketing scans of a nearby compact calibrator sources.

After calibration, we imaged the SNe. If there was sufficient flux density in the field, self-calibration in phase was attempted. However, the improvements in the SN images achieved by self-calibration ranged from non-existent to insignificant, suggesting that our initial phase-calibration is generally adequate for our purposes. Both the effective resolution and image background rms values varied from one SN to the other. The FWHM areas of the convolving beam ranged from $\sim 3.5$ to $\sim 12$ square arcseconds, and image rms values from $\sim 50$ to $\sim 100 \mu$Jy bm$^{-1}$. We can consider the SN positions accurately known for our purposes, since the coordinates of the SNe were obtained from optical observations, and are usually accurate to an arcsecond or better, and the position errors due to the VLA phase referencing are also expected to by $< 1''$, whereas the FWHM resolution of the radio observations was mostly $> 2''$.

### 2.2 VLA survey results

We present our flux density measurements, or upper limits, for each of the SNe in Table 1. As an uncertainty in the flux density we take the background rms or the radio image. With the exception of SN 2003gk, which is discussed below, we detected none of our sample SNe. Since, as mentioned, the SN positions are accurately known, we take the brightness of the radio image at the SN position as an estimate of the SN’s flux density. If this flux density is less than the flux-density uncertainty, we give only 3$\sigma$ upper limit on the flux density in Table 1. In the cases where the flux density exceeds the image rms, we add the estimate of the flux density as well as its uncertainty in addition to the 3$\sigma$ limit.

The only reliably detected source was SN 2003gk. The observed morphology is consistent with being unresolved (as expected), with a flux density of 2260$\pm$130 $\mu$Jy bm$^{-1}$, where the uncertainty consists of the image rms and a 5% calibration uncertainty added in quadrature.

For the other 58 SNe, the 3$\sigma$ upper limits given in Table 1 are conservative upper limit on the flux density of the SN since the presence of extended emission due to the galaxy cannot be ruled out. We note that in several cases, galactic emission is clearly seen at the SN location, and our limit on the SN emission is the limit on any compact emission in excess of the galactic emission at the SN location. No unresolved sources (except for SN 2003gk) were seen within several arcseconds of the nominal locations of any of our SNe.

From our measurements and limits to the flux density, we calculate the corresponding values of or limits on the radio spectral luminosity at 8.5 GHz using the distances indicated in Table 1. We plot these values in Figure 1. The luminosity of SN 2003gk was $(5.6 \pm 0.3) \times 10^{27} \text{ erg s}^{-1} \text{ Hz}^{-1}$ (where the uncertainty does not include any uncertainty in the distance, which was taken to be 44 Mpc).

We note that our survey is similar to that of Soderberg et al. (2006b), who also obtained upper limits on the 8.5-GHz flux density and thus radio luminosity of Type I b/c SNe at late times. We in fact re-observed fourteen SNe from that earlier survey: SN 2001ej, SN 2001is, SN 2002J, SN 2002bl, SN 2002cp, SN 2002dh, SN 2002ho, SN 2002hy, SN 2002hz, SN 2002ji, SN 2002jii, SN 2002jp, SN 2003dr, and SN 2003jd. Our flux-density limits were broadly similar to those of Soderberg et al. (2006b), but our observations occurred about 5.5 years later than theirs, and thus set upper limits on a much later part of the lightcurve.

## 3 SN 2003GK

### 3.1 Additional VLA observations and radio lightcurve of SN 2003gk

SN 2003gk was the only supernova detected in our radio survey. It was discovered by the Katzmann Automatic Imaging Telescope (KAIT) on 2003 July 1.5 (UT) with an unfiltered
magnitude of 17 (Graham & Li 2003a,b). Nothing was seen at its location on a KAIT image from 2002 Dec. 3.2 to magnitude ~19, and an optical spectrum by Matheson et al. (2003) showed it to be probably of Type Ib, resembling SN 1984L several weeks after maximum light, suggesting an explosion date around 2003 June 01 (MJD = 52792), which date we adopt here. Sollerman et al. (2003), deduced a relatively low expansion velocity of ~8300 km s$^{-1}$ from the minimum of the He I 587.6-nm absorption trough. The SN occurred in the Sc galaxy NGC 7460, which is at a distance of 45 Mpc (HyperLeda, Paturol et al. 2003)$^1$ In order to confirm our radio detection and to determine a light-curve and a measure of the radio spectral index, we obtained two additional

Table 1. Observed Supernovae

| Supernova | Galaxy | Type$^a$ | $D^b$ (Mpc) | Age$^c$ (yr) | 8.5-GHz Flux Density$^d$ (µJy) |
|-----------|--------|---------|-------------|-------------|-------------------------------|
| SN 2001aj | UGC 3829 | Ib | 57 | 7.7 | <145 |
| SN 2001iJ | NGC 1961 | Ib | 56 | 7.4 | <161 |
| SN 2002bl | UGC 5499 | Ib/BL | 71 | 7.3 | <246 (87 ± 53) |
| SN 2002bW | NGC 3974 | Ib | 76 | 7.2 | <263 |
| SN 2002hf | MCG-05-3-20 | Ib | 76 | 6.6 | <241 |
| SN 2002hn | NGC 2532 | Ib | 75 | 6.6 | <93 |
| SN 2002ho | NGC 4210 | Ib | 43 | 6.7 | <266 |
| SN 2002hy | NGC 3464 | Ib/pec | 56 | 6.6 | <247 |
| SN 2002iz | UGC 12044 | Ib | 76 | 6.7 | <195 |
| SN 2002jI | NGC 3655 | Ib/c | 28 | 6.5 | <272 |
| SN 2002jJ | IC 340 | Ib | 55 | 6.5 | <208 |
| SN 2002jP | NGC 3313 | Ib | 55 | 6.6 | <227 |
| SN 2003JH | NGC 2207 | Ib/pec | 38 | 6.4 | <188 |
| SN 2003Sr | NGC 5714 | Ib/c/pec | 38 | 6.2 | <177 |
| SN 2003gf | MCG-04-52-26 | Ib | 37 | 6.1 | <213 |
| SN 2003gk | NGC 7460 | Ib | 24 | 5.0 | <314 |
| SN 2003hp | UGC 10942 | Ib/BL | 93 | 5.9 | <208 |
| SN 2003id | NGC 895 | Ib/pec | 30 | 5.7 | <276 |
| SN 2003ig | UGC 2971 | Ib/c | 79 | 5.8 | <255 |
| SN 2003ih | UGC 2836 | Ib/c | 68 | 5.7 | <120 |
| SN 2003id | NGC 132 | Ib/BL | 77 | 5.7 | <172 |
| SN 2003ig | NGC 2997 | Ib/c | 13 | 5.7 | <330 |
| SN 2003ao | UGC 10862 | Ib | 30 | 5.4 | <256 |
| SN 2003av | NGC 3997 | Ib/BL | 73 | 5.1 | <211 |
| SN 2004em | NGC 3437 | Ib | 24 | 5.0 | <314 |
| SN 2004rf | UGC 8739 | Ib | 77 | 5.3 | <460 (154 ± 102) |
| SN 2004hs | NGC 3323 | Ib | 77 | 5.2 | <246 |
| SN 2004hu | UGC 10889 | Ib/BL | 84 | 5.0 | <244 |
| SN 2004hn | UGC 2069 | Ib | 51 | 4.9 | <196 |
| SN 2004ke | NGC 132 | Ib | 72 | 4.6 | <274 |
| SN 2004qG | NGC 3555 | Ib | 67 | 4.6 | <180 |
| SN 2004qg | NGC 4038 | Ib | 23 | 4.5 | <530 |
| SN 2004Qv | NGC 856 | Ib | 79 | 4.5 | <280 (106 ± 58) |
| SN 2005E | NGC 1032 | Ib/c | 36 | 4.4 | <267 |
| SN 2005N | NGC 5420 | Ib/c | 76 | 4.8 | <285 |
| SN 2005Y | NGC 2146 | Ib/c | 17 | 4.4 | <750 |
| SN 2005aj | UGC 2411 | Ib | 38 | 4.4 | <143 |
| SN 2005ct | NGC 207 | Ib | 54 | 4.0 | <327 |
| SN 2005aIa | UGC 11301 | Ib/BL | 68 | 3.9 | <309 |
| SN 2005bg | ESO 426-3 | Ib | 56 | 3.9 | <370 (121 ± 83) |
| SN 2005ek | UGC 2526 | Ib | 67 | 3.7 | <171 |
| SN 2005eo | UGC 4132 | Ib | 74 | 3.8 | <200 |
| SN 2005kz | MCG+08-34-32 | Ib/BL | 115 | 3.6 | <242 |
| SN 2005V | ESO 492-02 | Ib | 36 | 3.5 | <185 |
| SN 2006F | NGC 935 | Ib | 55 | 3.5 | <268 |
| SN 2006ab | PGC 10652 | Ib | 68 | 3.3 | <159 |
| SN 2006dg | IC 1568 | Ib | 58 | 3.2 | <180 |
| SN 2006ej | UGC 12287 | Ib | 73 | 3.2 | <195 |
| SN 2006eg | CCCCG462-023 | Ib/c | 53 | 2.9 | <214 |
| SN 2006ep | NGC 214 | Ib | 61 | 2.7 | <284 |
| SN 2007D | UGC 2653 | Ib/BL | 93 | 2.5 | <171 |
| SN 2007Y | NGC 1187 | Ib | 18 | 2.3 | <177 |
| SN 2007qj | UGC 3416 | Ib | 57 | 1.9 | <126 |
| SN 2007Ke | NGC 1129 | Ib | 70 | 1.7 | <146 |
| SN 2007ru | UGC 12381 | Ib/BL | 64 | 1.5 | <232 |
| SN 2007zA | NGC 1590 | Ib | 52 | 1.6 | <170 |
| SN 2008Dr | NGC 7422 | Ib | 66 | 0.9 | <412 (136 ± 92) |
| SN 2008qM | NGC 1343 | Ib | 33 | 1.0 | <450 |

$^a$ The SN type, taken from Barbon et al. (2010), with “BL” indicating a broadline SN
$^b$ The age of the SN, since estimated shock breakout or detection the date of observation, on 2009 May 25
$^c$ The distance to the SN, derived from the NED database
$^d$ The observed 8.5 GHz flux density and its uncertainty, or the 3σ upper on it
$^e$ The flux density from the SN has been corrected for significant radio emission from the galaxy at the location of the SN

$^1$ The distance is derived from the measured radial velocities, corrected for the local cluster’s infall velocity to Virgo; obtained from the HyperLeda database at http://leda.univ-lyon1.fr.
Figure 1. The detection of, and upper limits on the late-time radio emission of Type b/c SNe. We plot the 8.5 GHz spectral luminosity of the sole detection in our sample, SN 2003gk, in blue (note that the error bars are comparable in size to the plotted symbol), and the 3σ upper limits for the remaining 58 SNe as red triangles. Broad-lined SNe are marked with larger triangles.

3.2 VLBI observations

In order to determine the size of the radio emitting region in SN 2003gk, and thus to determine its average expansion speed, we obtained 8.4-GHz VLBI imaging observations of it on 2011 April 21 (observing code BB296), with a total time of 5 hours. The midpoint of the observations was at MJD 55673. We used the High-Sensitivity Array, which consisted of the NRAO VLBA (8 × 25-m diameter; the Pie Town and North Liberty antennas did not take part in this run), the NRAO Robert C. Byrd ∼105 m telescope at Green Bank, the Effelsberg (100 m diameter) telescope and the Arecibo (305-m diameter) telescopes.

We recorded a bandwidth of 64 MHz in both senses of circular polarization with two-bit sampling, for a total
We phase-referenced our VLBI observations to QSO J2257+0243, which is an ICRF source for which we use the position RA = 22^h 57^m 17.563103, dec. = 02° 43' 17" 51172 (J2000) (Fey et al. 2004). We used a cycle time of ~3.9 min, with ~2.4 min spent on SN 2003gk. We discarded any SN 2003gk data taken at elevations below 10°. In addition, we also spent two periods of ~10 min observing an astrometric check source JVAS J2258+0203, phase-referenced to J2257+0243 in the same manner as SN 2003gk.

We found that on both our check source, JVAS J2258+0203, and for SN 2003gk, the visibility phases for baselines involving Arecibo (AR) showed large residuals, suggesting that phase referencing at AR was not successful, and we therefore did not use the AR data for any astrometric results.

For marginally resolved sources, such as SN 2003gk, the best values for the source size come from fitting models directly to the visibility data, rather than from imaging. We chose as a model the projection of an optically-thin spherical shell of uniform volume emissivity, with an outer radius of 1.25 × the inner radius. Such a model has been found to be appropriate for other radio SNe (see e.g. Bietenholz, Bartel & Rupen 2003; Bartel & Bietenholz 2008). The Fourier transform of this shell model is then fitted to the visibility measurements by least squares.

We obtained a value of 0.37 mas for the outer angular radius of SN 2003gk. We also fitted the same shell model, but added antenna amplitude gains (non time-dependent scale factors) as free parameters, which changed the fitted outer radius by ~0.06 mas. Since the signal-to-noise ratio is too low to allow reliably fitting antenna gains (a form of amplitude self-calibration) we keep the original value of 0.37 mas as our best fit value, but take as a conservative uncertainty the 0.06 mas difference between the value obtained with the antenna gains added as free parameters and the original one. This value is approximately twice as large as the purely statistical uncertainty. We therefore take the final fitted value of the outer angular radius of SN 2003gk as 0.37 ± 0.06 mas.

For a partially resolved source such as SN 2003gk, the exact model geometry is not critical, and our shell model will give a reasonable estimate of the size of any circularly symmetric source, with a scaling factor of order unity dependent on the exact morphology (see discussion in Bartel et al. 2002). In particular, using a circular Gaussian model instead of the spherical shell model would result in a fitted size which is not very different. For a partially resolved source such as SN 2003gk, the exact model geometry is not critical, and our shell model will give a reasonable estimate of the size of any circularly symmetric source, with a scaling factor of order unity dependent on the exact morphology (see discussion in Bartel et al. 2002). In particular, using a circular Gaussian model instead of the spherical shell model would result in a fitted size which is not very different.

**Table 2.** Flux Density Measurements of SN 2003gk

| Date     | MJD   | Frequency (GHz) | Flux Density^a | \(\mu\text{Jy}\) |
|----------|-------|----------------|----------------|--------------|
| 2003 07 14 | 52834 | 8.46           | < 1980^b       |              |
| 2009 05 29 | 54981 | 8.46           | 2280 ± 110     |              |
| 2010 05 02 | 55518 | 8.46           | 2300 ± 130     |              |
| 2010 05 02 | 55518 | 22.46          | 1360 ± 90      |              |
| 2012 05 30 | 56077 | 8.46           | 1450 ± 80      |              |
| 2012 05 30 | 56077 | 21.36          | 0960 ± 50      |              |

^aThe listed uncertainties include an assumed 5% uncertainty in the flux density calibration.
^b 3σ upper limit.

Figure 3. A VLBI image of SN2003gk taken on 2011 Apr 21. The contours are drawn at -20, 20, 30, 50, 70 and 90% of the peak brightness, which was 86 \(\mu\text{Jy \cdot bm}^{-1}\). The rms background brightness was 51 \(\mu\text{Jy bm}^{-1}\). The FWHM restoring beam of 2.16 mas x 0.43 mas is indicated at lower left. North is up and east is to the left, and the coordinate origin is the brightness peak of SN 2003gk, which was at RA = 23^h 01^m 42.98207, dec = 02° 16' 08" 6798 (J2000). The dashed circle shows a circle of one light-year radius, showing the expected size of a source which has expanded relativistically for one year.
FWHM size of 0.5 mas, with the same relative uncertainty of 16%. We also attempted a fit of an elliptical Gaussian to model a possibly elongated source. To reduce the number of free parameters we fixed the axis ratio to 0.2. We obtained a FWHM major axis size of 0.61 \pm 0.10 mas.

Our fitted angular outer radius for SN 2003gk was 0.37 \pm 0.06 mas (for a spherical shell model). At a distance of 44 Mpc, this corresponds to (2.4 \pm 0.4) \times 10^{17} \text{ cm}.

The age of the SN at the time of the VLBI observations was 2881 days, so the average expansion velocity was (1.0 \pm 0.2) \times 10^{4} \text{ km s}^{-1}. The measured radius is not compatible with any relativistic, or near-relativistic expansion: at an apparent speed of c it would have reached our measured size at t = 96 d, so any reasonable non-relativistic expansion speed in the \sim 7.5 yr since then would have increased the size well beyond our measured value. The measured size is, however, entirely compatible with the expansion velocities of ordinary, non-relativistic SNe (e.g. Bietenholz 2005; Bartel 2009). Our VLBI measurements, therefore, exclude any relativistically expanding jet component in SN 2003gk. Unfortunately, with only single epoch of VLBI observations, we cannot constrain the proper motion.

4 CALCULATION OF MODEL LIGHTCURVES

The association of GRBs with massive stars implies that the afterglow shock propagates into the pre-explosion stellar wind, and suggests a stratified external medium with a density profile \rho_{\text{ext}} = A/r^{k}. If the ratio of wind velocity, \nu_{w}, to mass-loss rate, \dot{M}_{w}, remains constant, then k = 2 and A = \dot{M}_{w}/(4\pi\nu_{w}) = 5 \times 10^{13} A_{\odot} \text{ cm}^{-1}. Since \dot{M}_{w}/\nu_{w} might vary before the SN explosion, and is rather uncertain, other values of k have also been considered both in modelling of GRB afterglows (e.g. Yost et al. 2003; Starling et al. 2008; Leventis et al. 2012, 2013) and recently also in hydrodynamic simulations (De Colle et al. 2012b).

Nonetheless, most afterglow lightcurves calculated so far, and in particular those from hydrodynamic simulations, have been done for a uniform external medium (k = 0). Therefore, we present here results for a wind-like external medium of constant \dot{M}_{w}/\nu_{w} (i.e. k = 2), as a representative value for what might more realistically be expected for the wind of a massive star progenitor.

The typical value of the external density normalization parameter, A, is usually taken to be 1.0 in modelling, although the values that are inferred from afterglow broad-band modelling range from A \sim 1 down to less than 0.01. (Kumar & Pian et al. 2003; Waxman 2004b; Chevalier, Li & Fransson 2004; Rol et al. 2007; Racusin et al. 2008; Pandey et al. 2009; Cenko et al. 2010, 2011).

The true jet kinetic energy is usually inferred to be E_{\text{jet}} \sim 10^{50} \text{ erg}, for bright well-monitored afterglows and up to \sim 10^{54} \text{ erg} for the most energetic afterglows (e.g. Panaitescu & Kumar 2001b, a; Yost et al. 2003; Cenko et al. 2010, 2011). However, low-luminosity GRBs that have a larger rate per unit volume extend this distribution down to \lesssim 10^{48} \text{ erg} (e.g. Hjorth 2013).

The shock-microphysics processes responsible for field amplification and particle acceleration are typically parametrized by the assumptions that the magnetic field everywhere in the shocked region holds a fraction \epsilon_{B} = 0.1 of the local internal energy density in the flow, and that the non-thermal electrons just behind the shock hold a fraction \epsilon_{e} = 0.1 of the internal energy and have a power-law energy distribution with N(E) \propto E^{-\delta}. When it is possible to infer the values of these microphysics parameters for particular bursts, they are typically in the ranges 10^{-5} \lesssim \epsilon_{B} \lesssim 10^{-1}, 10^{-2} \lesssim \epsilon_{e} \lesssim 10^{-0.5}, and 2 \lesssim p \lesssim 3 (e.g. Santana, Barniol Duran & Kumar 2013). We refer to the values E_{\text{jet}} = 2 \times 10^{51} \text{ erg}, A_{\ast} = 1, \epsilon_{B} = \epsilon_{e} = 0.1, which are often used in modelling, as the “canonical” values, although, as just mentioned, they are likely not representative of the majority of bursts.

We use 2D hydrodynamic simulations for k = 2 from De Colle et al. (2012b), based on the special relativistic hydrodynamics code Mezcal, and a complimentary code for calculating the radiation by post-processing the results of the numerical simulations (De Colle et al. 2012a). The GRB was initialized on a conical wedge of half-opening angle \theta_{0} = 0.2 rad, taken out of the spherical self-similar Blandford & McKee (1976) solution. The simulation starts when the Lorentz factor of the material just behind the shock was \Gamma = 20. The calculation of the synchrotron radiation is supplemented by adding the contribution from a Blandford & McKee (1976) conical wedge at earlier times, corresponding to 20 \leq \Gamma \leq 500 (which causes an artificially sharp transition in the lightcurve between the two at a rather early time). Our value of \theta_{0} = 0.1 corresponds to a beaming factor of f_{B} = 1 - \cos \theta_{0} \approx 0.02. The simulation was for E_{k,\text{iso}} = 10^{53} \text{ erg}, corresponding to E_{\text{jet}} = f_{B}E_{k,\text{iso}} \approx 2 \times 10^{51} \text{ erg}, and for A_{\ast} = 1.65, but was scaled to arbitrary values of E_{\text{jet}} and A_{\ast} using appropriate scaling relations from Granot (2012). We have fixed the power-law index of the accelerated electrons to p = 2.5 as a representative value.

Fig. 4 shows lightcurves for different viewing angles (\theta_{\text{obs}} = 0.0, 0.4, 0.8, \pi/2) for our optimistic model using the canonical parameters which produce relatively bright radio afterglow emission: \epsilon_{B} = \epsilon_{e} = 0.1, E_{k,\text{iso}} = 10^{53} \text{ erg}, and A_{\ast} = 1. In Fig. 5 we fix \epsilon_{B} = \epsilon_{e} = 0.1 (as well as \theta_{\text{obs}} = \pi/2) and show the effect of varying the jet energy (E_{k,\text{iso}} = 10^{51}, 10^{53} \text{ erg}) and the external density normalization (A_{\ast} = 0.01, 0.1, 1), to cover a range that might be considered more typical for GRB jets. Hydrodynamics features, such as the observed non-relativistic transition time (which typically corresponds to the peak of the lightcurve for large off-axis viewing angles) scales as \left( E_{k,\text{iso}}/A_{\ast} \right)^{1/(3-k)} and therefore they vary much more strongly for the wind-like external medium (as E_{k,\text{iso}}/A_{\ast} \sim 2) than for a uniform medium where they vary only as \left( E_{k,\text{iso}}/n_{\text{external}} \right)^{1/3}. Not only the peak time varies substantially, but also the peak flux, which depends very strongly on A_{\ast}. Fig. 6 fixes E_{k,\text{iso}} = 10^{52} \text{ erg} and A_{\ast} = 0.1 (as well as \theta_{\text{obs}} = \pi/2), and shows the dependence of the lightcurves on \epsilon_{B} and \epsilon_{e} when varying the latter two well within the typical range inferred from GRB afterglow observations (10^{-4} \lesssim \epsilon_{B} \lesssim 0.1 and 10^{-2} \lesssim \epsilon_{e} \lesssim 0.1). This variation also has a large effect on the flux-density normalization.

The peak time of the modelled lightcurves depends on \left( E_{k,\text{iso}}/A_{\ast} \right) and with larger values of this ratio producing later peaks. The lightcurve with the canonical values of E_{k,\text{iso}} = 10^{53} \text{ erg} and A_{\ast} = 1 peaks at t = 109 d with 8.4-GHz spectral luminosity, L_{8.4 \text{ GHz}} = 1.1 \times 10^{29} \text{ erg s}^{-1} \text{ Hz}^{-1}, while the faintest of the lightcurves, also with E_{k,\text{iso}} = 10^{53} \text{ erg} s^{-1} \text{ Hz}^{-1} but with A_{\ast} = 0.01 peaks at t = 1466 d.
Figure 4. The modelled 8.4-GHz lightcurves of relativistic jets for angles to the line of sight between 0 and $\pi/2$ radians, as indicated at top right. The lightcurves were calculated assuming a wind-stratified medium ($k = 2$) with $A_* = 1$ and $\epsilon_B = \epsilon_e = 0.1$ (see text § 4). The red triangles our upper limits while the blue point is the measured values for SN 2003gk, repeated from Figure 1 above. We add here the corresponding limits from Soderberg et al. (2006b, marked “S2006”) as green triangles. The larger triangles again represent broadlined SNe. Note that for 14 SNe, there are two separate limits, one from our observations and an earlier one from Soderberg et al. (2006b). Although some of our limits (red triangles) are above the modelled lightcurves, in each such case there is an earlier limit (green triangle) which is well below the modelled curves.

Figure 5. The modelled lightcurves for various possible explosion energies and circumstellar densities, all for an angle to the line of sight $\theta_{\text{obs}} = \pi/2$. The curves are for the indicated values of $E_{k,\text{iso}}$, the isotropic explosion energy in erg and for a circumstellar density parameter $A_*$. For comparison, we again plot the observed value for SN 2003gk and limits for the other SNe from our sample (see Figure 4).
Figure 6. The modelled lightcurves for various possible efficiencies of magnetic field generation ($\epsilon_B$) and particle acceleration ($\epsilon_e$) at the shock front. All the lightcurves are for a wind-stratified medium ($k = 2$), $A_* = 0.1$, $E_{k,\text{iso}} = 10^{52}$ erg and for $\theta_{\text{obs}} = \pi/2$. The lightcurves are shown for the indicated values of ($\epsilon_B$ and $\epsilon_e$). For comparison, we again plot the observed value for SN 2003gk and limits for the other SNe from our sample (see Figure 4).

and $L_{\text{8.4 GHz}} = 1.5 \times 10^{24}$ erg s$^{-1}$ Hz$^{-1}$. The lightcurve with $E_{k,\text{iso}} = 10^{51}$ erg and $A_* = 1$ peaks as early as 3 d with $L_{\text{8.4 GHz}} = 8 \times 10^{29}$ erg s$^{-1}$ Hz$^{-1}$. In addition, if either $\epsilon_B$ or $\epsilon_e$ are below the nominal values of 0.1, a fainter lightcurve results, and the delayed peak, which is characteristic of jets at large angles to the line of sight, becomes less prominent. This occurs since the peak frequency, $\nu_* \propto \epsilon_B^{-2/3}$, and therefore is lower and passes the frequency of observation earlier, before the time when the beaming cone of the jet’s radiation reaches our line of sight.

5 COMPARISON OF OBSERVED LIMITS TO MODEL LIGHTCURVES

We now compare the model lightcurves for relativistic jets at various angles to the line of sight to the measurements of the late time radio emission of Type I b/c SNe. We combine our own sample (section 2.2 above) with that of Soderberg et al. (2006b). Our combined sample consists of 126 upper limits on 112 different SNe (14 SNe have limits obtained at two different times). We exclude SN 2003gk from this discussion, because as we have shown, its radio emission is not due to a relativistic jet.

The model lightcurves are strongly dependent on the explosion energy, $E_{k,\text{iso}}$ and the circumstellar density normalization, $A_*$. We first adopt “canonical”, or optimistic, values of $E_{k,\text{iso}} = 10^{53}$ erg and $A_* = 1$, and show the resulting lightcurves, along with the observed upper limits, in Figure 4. If we assume that the jets are randomly oriented, and that the statistics are Gaussian, we can calculate the probability ($P$) that any such jet would be fall below the limits we measured for our sample of SNe. The SN most compatible with the canonical lightcurves by this criterion is the non-broadlined SN 1996D, with $P \approx 0.014$, while for broadlined SNe it is SN 2003hp with $P \approx 10^{-4}$. We can therefore conclude that the probability of any of 112 our SNe being as bright as our canonical lightcurves is $<2\%$, and that probability that any of the 13 broadlined SNe being as bright is $<10^{-1}$. Note that a few of the limits from this paper are above the model lightcurves, but only for SNe for which an earlier limit for the same SN from Soderberg et al. (2006b) was well below the model lightcurves (as noted, we exclude SN 2003gk here, which is well above the predicted lightcurves, but as we showed above does not have any relativistic jet).

The brightness of the model lightcurves, however, depends strongly on the explosion energy ($E_{k,\text{iso}}$) and the density of the circumstellar medium ($A_*$). The canonical values above were adopted for observed GRB afterglows, and almost certainly represent present particularly bright GRB jets rather than the typical ones. In Figure 5, we therefore show the model lightcurves for a variety of plausible values for $E_{k,\text{iso}}$ and $A_*$. As can be seen, regardless of the value of $A_*$, all the lightcurves with $E_{k,\text{iso}} = 10^{51}$ erg are compatible with most of our observed limits, and even the lightcurves with

\[ \begin{align*}
\epsilon_B &= 0.1, \epsilon_e = 0.1 \\
\epsilon_B &= 0.01, \epsilon_e = 0.1 \\
\epsilon_B &= 0.01, \epsilon_e = 0.01 \\
\epsilon_B &= 10^{-5}, \epsilon_e = 0.1 \\
\epsilon_B &= 10^{-4}, \epsilon_e = 0.01
\end{align*} \]
the canonical value of \( E_{\text{iso}} = 10^{53} \) erg are compatible with most of our limits provided that the CSM density is characterized by \( A_* \lesssim 0.1 \). Even for the canonical values of \( E_{\text{iso}} = 10^{53} \) erg and \( A_* = 1 \), the predicted lightcurves fall below many of our measured limits if either \( \epsilon_B \) or \( \epsilon_e \) is below the canonical value of 0.1, but still within the range inferred to actually occur in GRBs.

6 DISCUSSION

6.1 SN 2003gk

SN 2003gk was not detected in the radio early on, with an upper limit to the 8.4-GHz spectral luminosity of \( L_{\nu, 8.4 \text{GHz}} = 4 \times 10^{25} \) erg s\(^{-1}\) Hz\(^{-1}\) at \( t = 29 \) d. By \( t = 2881 \) d, the radio luminosity had risen to \( \sim 4 \times 10^{26} \) erg s\(^{-1}\) Hz\(^{-1}\), and appeared to be decaying rapidly, with \( L_{\nu, 8.4 \text{GHz}} \propto t^{1.7 \pm 0.3} \) between \( t = 2510 \) and 3270 d. The spectral index between 8.4 and 22 GHz was \( -0.6 \pm 0.2 \).

Our VLBI measurements (section 3.2) showed that SN 2003gk was expanding non-relativistically, with an average speed of \( (1.0 \pm 0.2) \times 10^4 \) km s\(^{-1}\). If we assume a power-law expansion, with radius \( \propto t^{m} \) and take a typical value of 0.8 (see, e.g. Weiler et al. 2002) for the deceleration parameter, \( m \), then we can calculate that the initial speed (\( t = 0 \)) was 20,000 km s\(^{-1}\). If we take the expansion speed of SN 2003gk to have been 42,000 km s\(^{-1}\), we can calculate that SN 2003gk must have been fairly strongly decelerated, with \( m \approx 0.6 \).

We mentioned SN 2001em earlier, which showed a similar evolution in flux-density, but for which the VLBI observations also implied only non-relativistic expansion. We propose for SN 2003gk an explanation similar to that proposed for SN 2001em (see Chugai & Chevalier 2006; Chevalier 2007), namely that the radio emission is produced by the interaction of a normal Type I b/c ejecta with a massive and dense circumstellar shell at some distance from the progenitor. The shell was the result of episodic mass-loss from the progenitor, perhaps from a luminous blue variable like eruptive event. A possible further diagnostic would be if SN 2003gk were to show strong H\( \alpha \) emission, with a relatively narrow line width, which would be expected to accompany the strong circumstellar interaction.

6.2 What fraction of Type I b/c SNe host a GRB?

We carried out a survey for late-onset radio emission in Type I b/c SNe that might be indicative of an off-axis relativistic jet. Only one of our 59 SNe, SN 2003gk, showed any such radio emission, but our VLBI observations of it rule out relativistic expansion. It is clear therefore, that regardless of orientation, only a small fraction of Type I b/c have a relativistic jet producing bright late-time radio emission, or in other words host a GRB event. This conclusion was already reached earlier, in particular by Soderberg, Frail & Wieringa (2004); Soderberg et al. (2006b). We have combined our present sample with that of Soderberg et al. (2006b), for a combined set of 112 Type I b/c SNe which have been examined for radio emission such as might arise from an off-axis relativistic jet.

We compared limits on radio emission obtained for this combined sample to model lightcurves for relativistic jets at various angles to the line of sight (section 5), using numerically modelled lightcurves based on hydro-dynamic simulations, rather than the semi-analytic ones of Soderberg et al. (2006b).

On the basis of our results, the hypothesis that all Type I b/c SNe have radio lightcurves as bright as the canonical models with \( E_{\text{iso}} = 10^{53} \) erg, \( A_* = 1 \), and \( \epsilon_B = \epsilon_e = 0.1 \) can be rejected with a high level of confidence. Our sample included 13 broad-lined Type I b/c SNe, and we can also reject the hypothesis that all broadlined SNe have such bright radio lightcurves. We performed Monte-Carlo simulations with 10,000 trials, a randomly chosen fraction \( f_{\text{bright}} \) of our sample of 112 SNe having lightcurves as bright as our canonical models for each trial, with the remainder being unobservably faint. We then compared the simulated brightness values to our observed values or limits, and calculated the probability of that particular trial given the observed values and the uncertainties (assuming a Gaussian distribution for the measurement errors with the values of \( \sigma \) given or implied by the listed 3\( \sigma \) limit in Table 1). We performed such simulations for various values of \( f_{\text{bright}} \), with the result that we can say (at the 99% confidence level) that fewer than 5% (i.e. \( f_{\text{bright}} < 0.05 \)) of all Type I b/c SNe, and fewer than 33% of broad-lined SNe have radio lightcurves as bright as those produced by our canonical models. Our conclusions are consistent with those of Soderberg et al. (2006b), who concluded that at most 10% of all Type I b/c SNe are associated with “typical” GRB jets regardless of orientation, where their “typical” GRB jets have radio luminosities similar to those of the canonical models. Soderberg et al. (2006b) further concluded that even of the broadlined SNe, at most a fraction can be associated with a GRB jet.

Our results are also in agreement with the conclusions of Ghirlanda et al. (2013) who compared a simulated population of GRBs\(^5\) to samples of observed GRBs from Swift, Fermi GBM and CGRO BATSE (1177 GRBs in total). They found that to match the observed rates of bright GRB detections, the rate of GRB events (at any orientation) was \( \sim 0.3\% \) the rate of local Type I b/c SNe, and \( \sim 4.3\% \) that of local BL SNe. Although their constraint on the fraction of Type I b/c SNe accompanied by a bright GRB are tighter than ours, the two estimates are complimentary, since the two estimates have differing model dependencies. In particular, the radio observations are sensitive to jets with wide range of \( \Gamma \), whereas the observational constraints used by Ghirlanda et al. were restricted to highly relativistic jets with \( \Gamma \gtrsim 100 \).

However, the conclusion that the absence of late-time radio emission rules out off-axis GRB bursts in most type I b/c SNe are based on the assumption of a fairly bright jet, comparable to the detected GRB afterglows. Many of the

\(^5\) Ghirlanda et al. (2013)’s synthesized a population of GRBs under the assumption that, in the rest frame, all GRBs emit a total gamma-ray energy of \( 1.5 \times 10^{48} \) erg have an \( \nu F_{\nu} \) spectrum that peaks at 1.5 keV.
Radio limits on off-axis GRB afterglows and VLBI observations of SN 2003gk

Radio limits on off-axis GRB afterglows and VLBI observations of SN 2003gk

Radio limits on off-axis GRB afterglows and VLBI observations of SN 2003gk
a cooperative agreement with the National Science Foundation (AST-1100968), and in alliance with Ana G. Méndez Universidad Metropolitana and the Universities Space Research Association. We have made use of NASA’s Astrophysics Data System Bibliographic Services, the HyperLeda database and the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

Barbon R., Buondi V., Cappellaro E., Turatto M., 2010, VizieR Online Data Catalog, 1, 2024
Bartel N., 2009, in Astronomical Society of the Pacific Conference Series, Vol. 402, Approaching Micro-Arcsecond Resolution with VSOP-2: Astrophysics and Technologies, Hagiwara Y., Fomalont E., Tsuboi M., Yasuhiro M., eds., p. 243
Bartel N., Bietenholz M. F., 2008, ApJ, 682, 1065
Bartel et al., 2002, ApJ, 581, 404
Bietenholz M., 2005, in ASP Conf. Ser. 340: Future Directions in High Resolution Astronomy, Romney J., Reid M., eds., p. 286
Bietenholz et al., 2010a, in 10th European VLBI Network Symposium and EVN Users Meeting: VLBI and the New Generation of Radio Arrays
Bietenholz M. F., 2014, PASA, 31, 2
Bietenholz M. F., Bartel N., 2005, ApJL, 625, L99
Bietenholz M. F., Bartel N., 2007, ApJL, 665, L47
Bietenholz M. F., Bartel N., Rupen M. P., 2002, ApJ, 581, 1132
Bietenholz M. F., Bartel N., Rupen M. P., 2003, ApJ, 597, 374
Bietenholz M. F., Bartel N., Rupen M. P., 2010, ApJ, 712, 1057
Bietenholz M. F. et al., 2010b, ApJ, 725, 4
Blandford R. D., McKee C. F., 1976, Physics of Fluids, 19, 1130
Cenko S. B. et al., 2011, ApJ, 732, 29
Cenko S. B. et al., 2010, ApJ, 711, 641
Chandra P., Frail D. A., 2012, ApJ, 746, 156
Chevalier R. A., 1982, ApJ, 259, 302
Chevalier R. A., 1998, ApJ, 499, 810
Chevalier R. A., 2007, in Revista Mexicana de Astronomia y Astrofisica, vol. 27, Vol. 30, Revista Mexicana de Astronomia y Astrofisica Conference Series, pp. 41–48
Chevalier R. A., Fransson C., 2006, ApJ, 651, 381
Chevalier R. A., Li Z., Fransson C., 2004, ApJ, 606, 369
Chugai N. N., Chevalier R. A., 2006, ApJ, 641, 1051
Cobb B. E., Bloom J. S., Perley D. A., Morgan A. N., Cenko S. B., Filippenko A. V., 2010, ApJL, 718, L150
Corci A. et al., 2014, ApJ, 782, 42
De Colle F., Granot J., López-Cámara D., Ramirez-Ruiz E., 2012a, ApJ, 746, 122
De Colle F., Ramirez-Ruiz E., Granot J., Lopez-Cámara D., 2012b, ApJ, 751, 57
Fey A. L. et al., 2004, AJ, 127, 3587
Frail D. A. et al., 2001, ApJL, 562, L55
Gal-Yam A. et al., 2006, ApJ, 639, 331
Galama T. J. et al., 1998, Nat, 395, 670
Gehrels N., Ramirez-Ruiz E., Fox D. B., 2009, Ann. Rev. Astron. Astrophys., 47, 567
Ghirlanda G. et al., 2013, MNRAS, 428, 1410
Graham J., Li W., 2003a, Central Bureau Electronic Telegrams, 25, 1
Graham J., Li W., 2003b, IAU Circ., 8162, 2
Granot J., 2007, in Revista Mexicana de Astronomia y Astrofisica, vol. 27, Vol. 27, Revista Mexicana de Astronomia y Astrofisica, vol. 27, pp. 140–165
Granot J., 2012, MNRAS, 421, 2610
Granot J., Loeb A., 2003, ApJL, 593, L81
Granot J., Panaitescu A., Kumar P., Woosley S. E., 2002, ApJL, 570, L61
Granot J., Ramirez-Ruiz E., 2004, ApJL, 609, L9
Hjorth J., 2013, Royal Society of London Philosophical Transactions Series A, 371, 20275
Kumar P., Panaitescu A., 2003, MNRAS, 346, 905
Leventis K., van der Horst A. J., van Eerten H. J., Wijers R. A. M. J., 2013, MNRAS, 431, 1026
Leventis K., van Eerten H. J., Meliani Z., Wijers R. A. M. J., 2012, MNRAS, 427, 1329
MacFadyen A. I., Woosley S. E., Heger A., 2001, ApJ, 550, 410
Malesani D. et al., 2004, ApJL, 609, L5
Matheson T., Challis P., Kirshner R., Hicken M., Calkins M., 2003, IAU Circ., 8164, 2
McMullin J. P., Waters B., Schiebel D., Young W., Golap K., 2007, in Astronomical Society of the Pacific Conference Series, Vol. 376, Astronomical Data Analysis Software and Systems XVI, Shaw R. A., Hill F., Bell D. J., eds., p. 127
Mézéiros P., 2006, Reports on Progress in Physics, 69, 2259
Meunier C. et al., 2013, MNRAS, 431, 2453
Nakar E., Piran T., Granot J., 2002, ApJ, 579, 699
Paczyński B., 2001, Acta Astronomica, 51, 1
Panaitescu A., Kumar P., 2001a, ApJL, 560, L49
Panaitescu A., Kumar P., 2001b, ApJ, 554, 667
Pandey S. B. et al., 2009, Astron. Astrophys., 504, 45
Paragi Z. et al., 2010, Nat, 463, 516
Paturel G., Buondi V., Cappellaro E., Turatto M., 2010, VizieR Online Data Catalog, 1, 2024
Paczyński B., 2001, Acta Astronomica, 51, 1
Panaitescu A., Kumar P., 2001a, ApJL, 560, L49
Panaitescu A., Kumar P., 2001b, ApJ, 554, 667
Paragi Z. et al., 2010, Nat, 463, 516
Paturel G., Petit C., Prugniel P., Theureau G., Rousseau J., Brouty M., Dubois P., Cambrésy L., 2003, Astron. Astrophys., 412, 45
Pian E. et al., 2006, Nat, 442, 1011
Piran T., 2004, Reviews of Modern Physics, 76, 1143
Racusin J. L. et al., 2008, Nat, 455, 183
Rhoads J. E., 1997, ApJL, 487, L1
Røn E. et al., 2007, ApJ, 669, 1098
Salas P., Bauer F. E., Stockdale C., Prieto J. L., 2013, MNRAS, 428, 1207
Sanchez R., Barniol Duran R., Kumar P., 2013, ArXiv e-prints 1309.3277
Schinzel F. K., Taylor G. B., Stockdale C. J., Granot J., Ramirez-Ruiz E., 2009, ApJ, 691, 1380
Shahmoradi A., 2013, ApJ, 766, 111
Soderberg A. M., 2007, in American Institute of Physics Conference Series, Vol. 937, Supernova 1987A: 20 Years After: Supernovae and Gamma-Ray Bursters, Immler S., Weiler K., McCray R., eds., pp. 492–499
Soderberg A. M., Brumherler A., Nakar E., Chevalier R. A., Bietenholz M. F., 2010a, ApJ, 725, 922
Soderberg A. M. et al., 2010b, Nat, 463, 513

© 2011 RAS, MNRAS 000, 1–12
Soderberg A. M., Chevalier R. A., Kulkarni S. R., Frail D. A., 2006a, ApJ, 651, 1005
Soderberg A. M., Frail D. A., Wieringa M. H., 2004, ApJL, 607, L13
Soderberg A. M., Kulkarni S. R., Berger E., Chevalier R. A., Frail D. A., Fox D. B., Walker R. C., 2005, ApJ, 621, 908
Soderberg A. M., Nakar E., Berger E., Kulkarni S. R., 2006b, ApJ, 638, 930
Sollerman J., Andersson J., Gustafsson M., Jakobsson P., Oye G., Patat F., 2003, IAU Circ., 8164, 3
Stanek K. Z. et al., 2003, ApJL, 591, L17
Starling R. L. C., van der Horst A. J., Rol E., Wijers R. A. M. J., Kouveliotou C., Wiersema K., Curran P. A., Weltevrede P., 2008, ApJ, 672, 433
Starling R. L. C. et al., 2011, MNRAS, 411, 2792
van Eerten H., Zhang W., MacFadyen A., 2010, ApJ, 722, 235
van Eerten H. J., MacFadyen A. I., 2012, ApJ, 751, 155
van Paradijs J., Kouveliotou C., Wijers R. A. M. J., 2000, Ann. Rev. Astron. Astrophys., 38, 379
Wanderman D., Piran T., 2010, MNRAS, 406, 1944
Waxman E., 2004a, ApJL, 605, L97
Waxman E., 2004b, ApJ, 602, 886
Weiler K. W., Panagia N., Montes M. J., Sramek R. A., 2002, Ann. Rev. Astron. Astrophys., 40, 387
Woosley S. E., 1993, ApJ, 405, 273
Woosley S. E., Bloom J. S., 2006, Ann. Rev. Astron. Astrophys., 44, 507
Xu D. et al., 2013, ApJ, 776, 98
Yost S. A., Harrison F. A., Sari R., Frail D. A., 2003, ApJ, 597, 459
Zhang B., 2007, Advances in Space Research, 40, 1186