LETTERS

A mildly relativistic radio jet from the otherwise normal type Ic supernova 2007gr

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The class of type Ic supernovae have drawn increasing attention since 1998 owing to their sparse association (only four so far) with long duration γ-ray bursts (GRBs)[1–4]. Although both phenomena originate from the core collapse of a massive star, supernovae emit mostly at optical wavelengths, whereas GRBs emit mostly in soft γ-rays or hard X-rays. Though the GRB central engine generates ultra-relativistic jets, which beam the early emission into a narrow cone, no relativistic outflows have hitherto been found in type Ib/c supernovae explosions, despite theoretical expectations[5–7] and searches[8]. Here we report radio (interferometric) observations that reveal a mildly relativistic expansion in a nearby type Ic supernova, SN 2007gr. Using two observational epochs 60 days apart, we detect expansion of the source and establish a conservative lower limit for the average apparent expansion velocity of 0.6*c*. Independently, a second mildly relativistic supernova has been reported[9]. Contrary to the radio data, optical observations[10–13] of SN 2007gr indicate a typical type Ic supernova with ejecta velocities ~6,000 km s^{-1}, much lower than in GRB-associated supernovae. We conclude that in SN 2007gr a small fraction of the ejecta produced a low-energy mildly relativistic bipolar radio jet, while the bulk of the ejecta were slower and, as shown by optical spectropolarimetry[14], mildly aspherical.

On 2007 August 15.51 UT the Katzman Automatic Imaging Telescope (KAIT) discovered[15] SN 2007gr at magnitude 13.8 in the bright spiral galaxy NGC 1058, at a distance[16] of 10.6 ± 1.3 Mpc. At discovery, SN 2007gr was less than five days old, based on its non-detection with KAIT on 2007 August 10.44 UT. Later optical observations[11,12] firmly classified SN 2007gr as a type Ic stripped envelope core-collapse supernova. SN 2007gr was one of the closest of its kind. Radio observations[17] with the Very Large Array (VLA) on 2007 August 17 revealed a radio source with a flux density $F_{8.4\mathrm{GHz}} = 0.610 \pm 0.040$ mJy, thus making the source an ideal candidate for high-resolution radio imaging. The electronic very long baseline interferometry (e-VLBI) technique, which significantly improved the flexibility of the European VLBI network (EVN), enabled us to carry out sensitive high-angular-resolution observations soon after the discovery.

We observed SN 2007gr at 5 GHz with a subset of the EVN on 2007 September 6–7 for 11 h (~25 days after the supernova explosion), using the e-VLBI technique (see also Supplementary Information Sections 1 and 3). We detected a source with a peak brightness of 422 μJy per beam at 5.6 times the off-source noise level of 75 μJy per beam and determined an upper limit of 7 milliarcseconds (mas) for its angular diameter size (Fig. 1). At 10.6 Mpc, this corresponds to a linear (diameter) size of $<1.1 \times 10^{18}$ cm, which sets an upper limit of $\langle v_{\mathrm{app}} \rangle < 8.6c$ on the average isotropic apparent expansion speed of the ejecta.

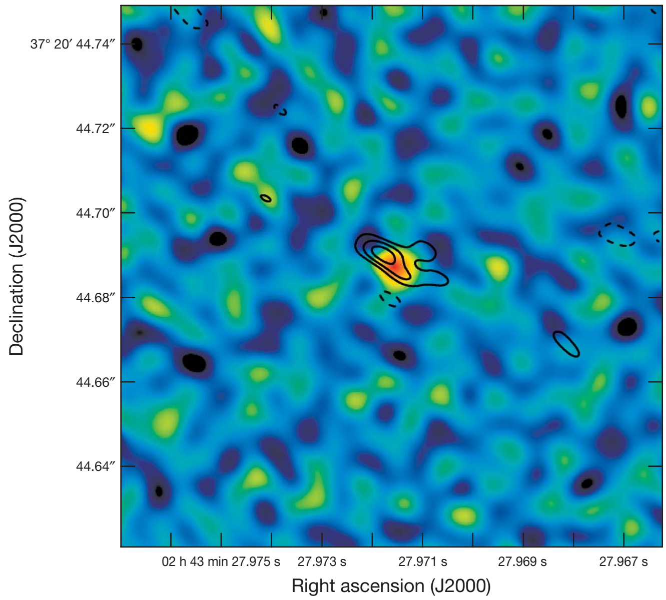

Figure 1 | EVN and EVN+GBT observations of SN 2007gr. The colours, ranging from −150 to 441 μJy per beam, show the map of SN 2007gr observed on 2007 September 6–7 at 5 GHz with the EVN using the e-VLBI technique. The off-source noise in the map is 75 μJy per beam, and the peak is 422 μJy per beam (5.6σ). The VLBI location of RA = 02 h 43 min 27.97151 s, dec. = +37° 20′ 44.6873″ (J2000) is consistent with the VLA coordinates RA = 02 h 43 min 27.972 s, dec. = +37° 20′ 44.677″ (J2000) obtained at a lower resolution. The black contours show the naturally weighted and tapered EVN+GBT image of SN2007gr on 2007 November 5–6. At this epoch the off-source noise is 13 μJy per beam, and the peak is 60 μJy per beam (4.7σ). The image is centred at the position measured by the EVN at the first epoch. The apparent position shift in the peak brightness from the centre indicates that at lower resolution there is some extended flux density detected near the supernova position. The restoring beam for this image is 15.26 × 6.85 mas at a position angle of 53.3°. The contours are drawn at −26, 26, 39 and 52 μJy per beam (corresponding to −2, 2, 3 and 4 σ).

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Our second observation was carried out with the EVN and the Green Bank Telescope (GBT) on 2007 November 5–6 for 10 h, ~85 days after the explosion (see also Supplementary Information Sections 2 and 3). We detected the supernova with a peak brightness of 60 μJy per beam (4.7σ) at 5 GHz with this sensitive VLBI network (Fig. 1). The observed peak brightness was significantly below the 260 μJy total flux density measurement of the Westerbork Synthesis Radio Telescope (WSRT), which is part of the VLBI network. Further confirmation of the WSRT flux density measurement was obtained from archival VLA data (Fig. 2), taken just 13 days after the second VLBI epoch, which measured a flux density of 250 ± 40 μJy at 5 GHz. Figure 2 shows a peak flux density of ~1 mJy at ~5 days, which corresponds to a peak luminosity of 1.3×10^{26} erg s^{-1} Hz^{-1}. Compared to other 'normal' Ib/c radio supernovae[18], this luminosity is at the lower end of the distribution (see also ref. 9).

Although part of the discrepancy between the VLBI peak brightness and the WSRT and VLA flux densities may be attributed to phase coherence losses, data simulations showed that this cannot explain such a dramatic decrease in the source peak brightness (see also Supplementary Information Section 4). Moreover, the first epoch e-VLBI run used exactly the same observing scheme, and it did not show any discrepancy between the VLBI and WSRT measurements. The best explanation for the apparently low peak brightness is that the source was resolved by the second VLBI observation. Under this assumption, we derive a conservative lower limit for the angular diameter size of 1.7 mas, which is the geometric mean of the major and minor axes of the beam. This corresponds to a linear size of 2.7×10^{17} cm, and a lower limit of $\langle v_{app} \rangle > 0.61c$ on the average apparent expansion speed (and $v > 0.52c$ for the true expansion speed). These results conservatively assume isotropic expansion (that is, half the diameter travelled in 85 days). Note that the actual size and average expansion speed are probably somewhat larger than this lower limit ($\langle v_{app} \rangle \approx c$ and $v \gtrsim 0.7c$). Furthermore, as we estimate the average expansion speed, and the emitting region is most likely to be decelerating at this stage (as suggested by the fading radio flux density), the initial velocity of the outflow powering this extended radio emission should be higher than this estimate, and similarly v_{app}(85 days) $< \langle v_{app} \rangle$. Further analysis of the data exploring various resolutions hints at an extension ~2.5 mas to the northeast of the supernova position, which would correspond to a linear offset of $\sim 4.0 \times 10^{17}$ cm and a (one-sided) superluminal average apparent expansion velocity of ~1.8c.

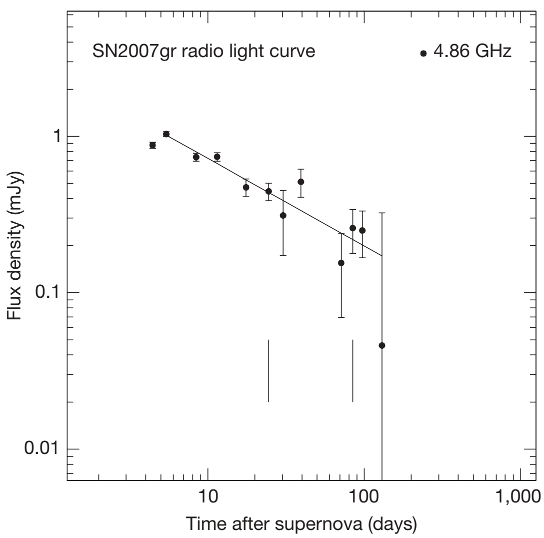

Figure 2 | VLA and WSRT light curve of SN 2007gr. The VLA observed SN 2007gr at 4.86 GHz between 2007 August 17 and 2007 December 21 on 10 separate occasions for a typical duration of 15 min each. In the first five epochs the VLA was in A configuration, then two observations were conducted in a hybrid (BnA) configuration, and the last three observations were carried out in B configuration. Flux densities for each epoch were derived from model fitting a single Gaussian component to the visibility data. We show here the light curve including the two WSRT observations (during the VLBI observations), indicated with two vertical lines. A power-law fit to all the data except the first point when the flux density was still rising is shown (solid line) and has a slope of -0.56 ± 0.06, with a reduced χ^2 value of 1.70. All times are referenced to 2007 August 13, presumed to be close to the time of the explosion. The error bars indicate 1σ uncertainties.

Apart from the mildly relativistic expansion of its radio emitting material, SN 2007gr appears normal, with photospheric expansion velocities smaller[12] than those inferred in hypernovae (broad-line type Ic supernovae), some of which are associated with GRBs. The radio synchrotron emission is already fading and optically thin several days after the explosion (with $F_\nu \propto \nu^{-0.66 \pm 0.15}$ on 2007 August 17, based on the fluxes in Fig. 2 and in ref. 17; here F_ν is spectral flux density and ν is frequency). This observation, combined with the lower limit on the source size at ~85 days ($v_{app} \approx 0.6$–1 c) sets a lower limit on the energy, E_{radio}, of the radio-synchrotron-emitting material, $E_{min} \approx (0.7\text{–}1.3) \times 10^{46} (10f)^{3/7}$ erg, where f is the fractional volume within the inferred source radius filled by the relativistic electrons and magnetic fields[6]. E_{min} corresponds to (almost) equipartition—equal energy in relativistic electrons and magnetic fields. A reasonable deviation from equipartition may result in $E_{radio}/E_{min} \approx 10$–$100$. For an initially relativistic flow of total energy E occupying a fraction f_Ω of the total solid angle, and expanding into an external medium with mass density $\rho = Ar^{-2}$, where r is the distance from the progenitor star, and A is a normalization factor, the flow becomes non-relativistic[6] at $t_{NR} = 2.3 E_{48} A_0^{-1} f_\Omega^{-1}$ days; here E_{48} is E in units of 10^{48} erg, and A_0 is A in units of 1.5×10^{10} g cm^{-1}. Our observations indicate $t_{NR} \approx 6$–27 days, suggesting either a spherical flow ($f_\Omega = 1$) with $E_{radio} \approx 10^{49}$ erg, where the electrons and magnetic field are very far from equipartition, or more plausibly, that the mildly relativistic outflow is collimated into narrow bipolar jets (for example, $f_\Omega \approx 0.03$ and $f \approx 0.1 f_\Omega$ give $E_{radio}/E_{min} \approx 10^2$ and E_{radio} as a few times 10^{47} erg). We note here that for SN 2007gr, $E_{min} \approx 10^{46}$ erg, which is a few times smaller than that inferred[4] for GRB 060218-SN 2006aj and a few orders of magnitude lower than the other secure GRB-SN associations[4]. Our observations thus suggest that the mildly relativistic radio-emitting material in SN 2007gr carries only a very small fraction ($\sim 10^{-4}$) of the total explosion energy, estimated to be a few times 10^{51} erg from optical observations[12].

Our discovery of the peculiar radio properties of SN 2007gr has important implications for the diversity of H-stripped core-collapse type Ic supernovae. Thus far we have seen: SN 2007gr, which might be the typical case (modest energy in (mildly) relativistic ejecta and no GRB); events like SN 2006aj/GRB 060218 (very dim GRB with very modest energy in relativistic ejecta); the hypernova-like SN 1998bw/GRB 980425 (dim GRB, but slightly more energy in relativistic ejecta); and last, SN 2003dh/GRB 030329 or GRBs at redshift $z \gtrsim 1$ ($E \gtrsim 10^{51}$ erg in relativistic ejecta). It is possible that all (or at least most) type Ic supernovae produce bipolar jets that are at least mildly relativistic, but that the relativistic energy content varies dramatically while the total explosion energy is much more standard. In this picture, most type Ic supernovae are likely to have very modest energy in relativistic material (and do not produce a GRB), making their radio emission detectable (and resolvable, as in SN 2007gr) only from a small local volume that implies a low detection rate; this explains why SN 2007gr is one of the two supernovae so far (besides SN 2009bb[9]) to show evidence for mildly relativistic expansion.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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