An optical supernova associated with the X-ray flash XRF 060218

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Long-duration γ-ray bursts (GRBs) are associated with type Ic supernovae[1] that are more luminous than average[2–5] and that eject material at very high velocities. Less-luminous supernovae were not hitherto known to be associated with GRBs, and therefore GRB–supernovae were thought to be rare events[6]. Whether X-ray flashes—analogues of GRBs, but with lower luminosities and fewer γ-rays—can also be associated with supernovae, and whether they are intrinsically 'weak' events or typical GRBs viewed off the axis of the burst[7], is unclear. Here we report the optical discovery and follow-up observations of the type Ic supernova SN 2006aj associated with X-ray flash XRF 060218. Supernova 2006aj is intrinsically less luminous than the GRB–supernovae, but more luminous than many supernovae not accompanied by a GRB. The ejecta velocities derived from our spectra are intermediate between these two groups, which is consistent with the weakness of both the GRB output[8] and the supernova radio flux[9]. Our data, combined with radio and X-ray observations[8–10], suggest that XRF 060218 is an intrinsically weak and soft event, rather than a classical GRB observed off-axis. This extends the GRB–supernova connection to X-ray flashes and fainter supernovae, implying a common origin. Events such as XRF 060218 are probably more numerous than GRB–supernovae.

The Burst Alert Telescope (BAT) onboard the Swift spacecraft detected XRF 060218 on 18 February 2006 at 03:34:30 UT (ref. 8). Its spectrum peaked near 5 keV, placing the burst in the XRF subgroup of GRBs. The optical counterpart of the burst was detected ~200 s later by the Swift Ultraviolet/Optical Telescope, and was subsequently observed by ground-based telescopes[11]. The closeness of the event[12] made XRF 060218 an ideal candidate for spectroscopic observations of a possible associated supernova.

We observed XRF 060218 with the European Southern Observatory's (ESO) 8.2-m Very Large Telescope (VLT) and the University of California's Lick Observatory Shane 3-m telescope (Lick) starting 21 February 2006. Supplementary Table 1 shows the log of the observations. Spectroscopy was performed nearly daily for seventeen days (see Supplementary Fig. 1). Broad absorption lines detected in our first spectrum resembled those of broad-lined type Ic supernovae, thus providing the first definite case of a supernova associated with an XRF[13]. To our knowledge, this is the earliest spectroscopy of a GRB–supernova, and one of the earliest for any supernova. From its early decline, we estimate that the contribution of the fading afterglow of XRF 060218 to the supernova emission is not significant at the epoch of our first spectrum[11,12].

The high-dispersion spectrum taken with the VLT Ultraviolet and Visual Echelle Spectrograph (UVES) near the epoch of supernova maximum exhibits several narrow emission and absorption lines. From the former we obtained an accurate measurement of the host-galaxy redshift, $z = 0.03342 \pm 0.00002$ (heliocentrically corrected), corresponding to a distance of ~140 Mpc (using a Hubble constant of $H_0 = 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_\Lambda = 0.72$, and $\Omega_\mathrm{m} = 0.28$). We constrained the total extinction toward the supernova from the equivalent widths of the interstellar Na I D absorption lines[14] to be $E(B - V) = 0.13 \pm 0.02$ mag (P.A.M., manuscript in preparation). The extinction is mainly due to our Galaxy, and its value is consistent with that derived using infrared dust maps[15]. We used this value to correct the light curve of SN 2006aj (Fig. 1).

It is interesting to compare the properties of SN 2006aj with those

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of other type Ic supernovae. The three well-observed, low-redshift GRB–supernovae (SN 1998bw, SN 2003dh and SN 2003lw) are strikingly similar. They are about 5–6 times more luminous and about 30 times more energetic than typical type Ic supernovae[16]. The peak luminosities and the kinetic energies of the GRB–supernovae differ by no more than 30%. At maximum light, SN 2006aj is dimmer than these supernovae by about a factor of two, but it is still a factor of 2–3 more luminous than other broad-lined type Ic supernovae not associated with GRBs and normal (narrow-lined) type Ic supernovae (Fig. 1).

Normal type Ic supernovae rise to a peak in approximately 10–12 days and have photospheric expansion velocities of $\sim$10,000 km s^{-1} after about 10 days. Previously known GRB–supernovae showed a longer rise time (14–15 days) and had, at an epoch of about ten days, velocities of $\sim$25,000 km s^{-1} (see Figs 1 and 2). If XRF 060218 and SN 2006aj occurred simultaneously, SN 2006aj rose as fast as normal type Ic supernovae, and also declined comparatively fast. At the same time, the photospheric expansion velocity derived from spectral modelling is intermediate between the GRB–supernovae and other type Ic supernovae, broad-lined or narrow-lined, that were not associated with GRBs (Fig. 2). Asymmetry in the supernova explosion may modify the observed luminosity with respect to the intrinsic one, depending on the orientation of the symmetry axis, by no more than 25% (ref. 17).

We conclude that SN 2006aj is intrinsically dimmer than the other three GRB–supernovae. In addition, it is associated with the softest (but not the weakest) of the four local events connected with supernovae[8], and it has mildly relativistic ejecta[8,9], thus appearing to be an intermediate object between GRB–supernovae and other type Ic supernovae, both broad-lined and narrow-lined, not accompanied by a GRB.

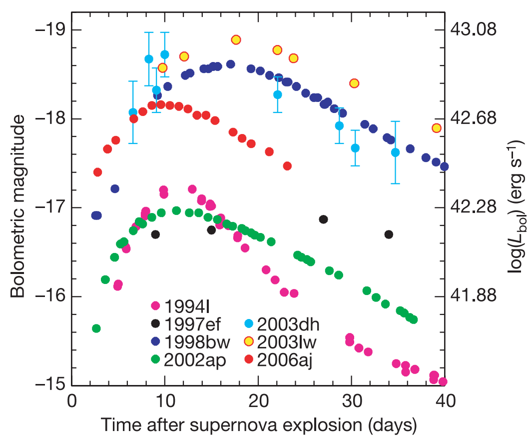

Figure 1 | Bolometric light curves of type Ic supernovae. We report, as a function of time, the luminosity and corresponding absolute magnitude of (1) the four spectroscopically identified supernovae associated with GRBs and XRFs, namely SN 1998bw (GRB 980425, $z = 0.0085$), SN 2003dh (GRB 030329, $z = 0.168$), SN 2003lw (GRB 031203, $z = 0.1055$), and SN 2006aj (XRF 060218, $z = 0.03342$); (2) of two broad-lined supernovae (not accompanied by a GRB), SN 1997ef and SN 2002ap; and (3) of the normal, intensively monitored SN 1994I. All represented supernovae are type Ic. The light curves, reported in their rest frame, have been constructed in the 3,000–24,000 Å range, taking into account the Galactic and, where appropriate, the host galaxy extinction[16,25–28]. For SN 2006aj, we used the optical light curves obtained during our monitoring and the near-infrared data reported by ref. 29, and a total extinction value of $E(B-V) = 0.13$ mag (see text). We adopted the extinction curve of ref. 30 with $R_V = 3.1$. The galaxy contribution has also been subtracted where significant. The initial time has been assumed to coincide with the XRF detection time, 18 February 2006 at 03:34:30 UT. The systematic errors (about 0.2 mag) have been omitted, for clarity. Error bars are 1σ. The shape of the light curve of SN 2006aj is similar to that of SN 2002ap, as are the spectra[18].

All together, these facts point to a substantial diversity between supernovae associated with GRBs and supernovae associated with XRFs. This diversity may be related to the masses of the exploding stars. In a companion paper, the parameters of the explosion are derived from models of the supernova optical light curves and spectra, and a relatively low initial mass, $20M_\odot$ (where $M_\odot$ is the mass of the sun), is proposed, evolving to a $3.3M_\odot$ CO star[18]. This mass is smaller than those estimated for the typical GRB–supernovae[19].

GRBs and GRB–supernovae are aspherical sources. If XRF 060218 was a normal GRB viewed off-axis, the observed soft flux was emitted at large angles with respect to its jet axis. If the associated SN 2006aj is aspherical, then it is also probably seen off-axis. Alternatively, XRF 060218 may have been intrinsically soft, whether it was an aspherical explosion viewed on-axis or a spherical event. Various independent arguments, such as the chromatic behaviour of the multiwavelength counterpart of XRF 060218 (ref. 8), the absence of a late radio rebrightening[9] and the compliance of XRF 060218 with the empirical correlation between peak energy and isotropic energy[10], favour the latter possibility.

Together with the observation of other underluminous, relatively nearby XRFs and GRBs—GRB 980425 (ref. 2), XRF 030723 (refs 20, 21), XRF 020903 (ref. 22), and GRB 031203 (refs 23, 24), some definitely and some probably associated with supernovae—the properties of XRF 060218 suggest the existence of a population of events less luminous than 'classical' GRBs, but possibly much more numerous and with lower radio luminosities[9]. Indeed, these events may be the most abundant form of X- or γ-ray explosive transient in the Universe, but instrumental limits allow us to detect them only locally, so that several intrinsically subluminous bursts may remain undetected. The fraction of supernovae that are associated with GRBs or XRFs may be higher than currently thought.

By including this underluminous population and assuming no correction for possible collimation, which may vary from object to object, we obtain a local GRB rate of 110^{+180}_{-20} Gpc^{-3} yr^{-1}, compared to 1 Gpc^{-3} yr^{-1} estimated from the cosmological events only (see Supplementary Information for details). In particular, for the detection threshold of Swift, we expect a few bursts per year within $z = 0.1$ and with luminosities as low as that of GRB 980425. The low-energy GRB population could be part of a continuum of explosion phenomena that mark the collapse of a stellar core, with normal supernovae at one end and classical GRBs at the other.

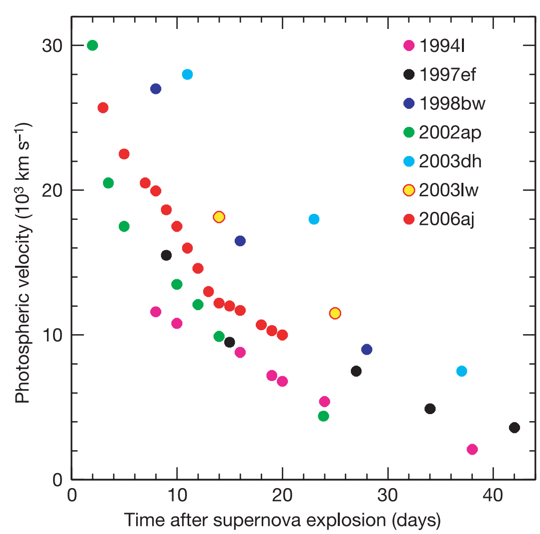

Figure 2 | Photospheric expansion velocities of type Ic supernovae. The time profiles of the expansion velocities of the same seven supernovae represented in Fig. 1 are reported. The velocities have been determined through models of the spectra at the various epochs[16,18,25,26].

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

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