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LETTERS

A neutron-star-driven X-ray flash associated with supernova SN 2006aj

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Supernovae connected with long-duration γ-ray bursts[1–3] (GRBs) are hyper-energetic explosions resulting from the collapse of very massive stars ($\sim 40\,M_\odot$, where $M_\odot$ is the mass of the Sun) stripped of their outer hydrogen and helium envelopes[4–7]. A very massive progenitor, collapsing to a black hole, was thought to be a requirement for the launch of a GRB[8]. Here we report the results of modelling the spectra and light curve of SN 2006aj (ref. 9), which demonstrate that the supernova had a much smaller explosion energy and ejected much less mass than the other GRB–supernovae, suggesting that it was produced by a star whose initial mass was only $\sim 20\,M_\odot$. A star of this mass is expected to form a neutron star rather than a black hole when its core collapses. The smaller explosion energy of SN 2006aj is matched by the weakness and softness[10] of GRB 060218 (an X-ray flash), and the weakness of the radio flux of the supernova[11]. Our results indicate that the supernova–GRB connection extends to a much broader range of stellar masses than previously thought, possibly involving different physical mechanisms: a 'collapsar' (ref. 8) for the more massive stars collapsing to a black hole, and magnetic activity of the nascent neutron star[12] for the less massive stars.

Like all other GRB–supernovae, SN 2006aj is of type Ic (ref. 9). Its spectra resemble those of the dim, broad-lined, non-GRB supernova SN 2002ap (refs 13, 14). However, SN 2006aj shows surprisingly weak oxygen lines for a type Ic supernova. For a comparison of the spectrum of SN 2006aj and those of SN 2002ap and of the GRB–supernova SN 1998bw, see Supplementary Information.

To reproduce the spectrum of SN 2006aj (ref. 9) we started from the model that was used for SN 2002ap (ref. 13), but to improve the spectral fits we reduced the masses of both oxygen and calcium significantly, and decreased the ejected mass M_{ej} and the kinetic energy E_{K} accordingly. The series of synthetic spectra is shown in Fig. 1.

A lack of oxygen lines in the spectrum suggests a small M_{ej}, but it does not necessarily mean absence of oxygen in the ejecta. Our model contains $\sim 1.3\,M_\odot$ of oxygen. Oxygen is therefore still the dominant element, but its abundance relative to other (heavier) elements is much lower than in SN 2002ap or in the other GRB–supernovae. Modelling also indicates that oxygen is confined to high velocities (Fig. 1). A shell of oxygen comprising $\sim 0.1\,M_\odot$ and expanding at velocities between 20,000 and 30,000 km s^{-1} is detected, which may be the result of the episode of interaction that was responsible for the early ultraviolet brightening[10].

The spectroscopic results are confirmed by models of the light curve. A synthetic light curve computed using the one-dimensional density and chemical abundance structure obtained from the spectral analysis reproduces the optical-infrared bolometric light curve of SN 2006aj (Fig. 2). For SN 2006aj we derive $M_{\mathrm{ej}} \approx 2\,M_\odot$ and $E_{\mathrm{K}} \approx 2 \times 10^{51}$ erg. These values are much smaller than those of the other GRB–supernovae, which typically have $M_{\mathrm{ej}} \approx 10\,M_\odot$ and $E_{\mathrm{K}} \approx 3 \times 10^{52}$ erg (refs 4–7). The smaller E_{K} and M_{ej} involved for SN 2006aj explain why the light curve evolves more rapidly than that of SN 2002ap: the timescale of the light curve depends in fact roughly on $M_{\mathrm{ej}}^3/E_{\mathrm{K}}$ (ref. 15). The supernova ejecta contain $0.21\,M_\odot$ of ^{56}Ni, which is responsible for the supernova luminosity. About $0.02\,M_\odot$ of this is located above 20,000 km s^{-1} and causes the fast rise of the light curve. The presence of ^{56}Ni at high velocities is unlikely to be the result of a spherically symmetric explosion. In a realistic aspherical explosion, high-velocity ^{56}Ni may be copiously produced near the direction of the GRB jets[16].

Observations in the nebular phase, when the forbidden [O I] 6,300 Å and 6,363 Å lines should be strong in emission, will be needed to determine more accurately the value of M_{ej}. Such observations, to be performed starting August 2006, will also be useful in studying any possible asymmetry and the orientation of the supernova with respect to the line of sight to the Earth, and thus to link the supernova with the GRB[16,17].

The properties of both the supernova (small energy, small ejected mass, low oxygen content) and of the GRB (unusually soft and long) seem to suggest that the GRB 060218–SN 2006aj event was not the same type of event as the other GRB–supernovae known thus far. The radio properties of SN 2006aj were also intermediate between those of the GRB–supernovae and of SN 2002ap (ref. 11).

One possibility is that the initial mass of the progenitor star was significantly smaller than in the other GRB–supernovae, and that the collapse/explosion generated less energy. A star with zero-age main-sequence mass of ~ 20–$25\,M_\odot$ would be at the boundary between collapse to a black hole or to a neutron star[18]. If the star collapsed only to a neutron star, more core material would be available to synthesize ^{56}Ni. For example, a star with initially $\sim 20\,M_\odot$ would develop a carbon–oxygen core of $\sim 3.3\,M_\odot$ (ref. 18). If core collapse left behind a neutron star of $\sim 1.4\,M_\odot$, $\sim 1.3\,M_\odot$ of oxygen and $\sim 0.6\,M_\odot$ of heavier elements (including both intermediate-mass elements such as Si and Fe-group elements) could be ejected in the supernova, consistent with our results. Such a collapse is thought to give rise to an explosion of $E_{\mathrm{K}} \approx 10^{51}$ erg (ref. 19), but there are indications of a spread in both E_{K} and the mass of ^{56}Ni synthesized[20]. Additionally, magnetar-type activity may have been present, increasing the explosion energy[12]. Magnetic activity may also have caused the very long duration of the γ-ray emission[12] and the mixing-out of ^{56}Ni required by the rapid rise of the light curve. It is also possible

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that in this weaker explosion the fraction of energy channelled to relativistic ejecta was smaller than in the classical GRB–supernova, giving rise to an X-ray flash (XRF)[11].

Another case of a supernova associated with an XRF has been reported[21]. The putative supernova, although poorly observed, was also most consistent with the properties of SN 2002ap (ref. 22). This may suggest that XRFs are associated with less-massive progenitor stars than those of canonical GRBs, and that the two groups may be differentiated by the formation of a magnetar[23] or a black hole, respectively. The properties of both the GRB and the supernova may scale with the mass of the progenitor[24]. Still, the progenitor of SN 2006aj had been thoroughly stripped of its H and He envelopes. This is a general property of all GRB–supernovae known so far, and possibly a requirement for the emission of a high-energy transient, which may be more easily achieved in a binary system[13,25,26].

If the star was initially more massive ($\gtrsim 25 M_\odot$), and it collapsed directly to a black hole as in the more powerful GRB–supernova events, a number of questions arise. Why was the energy of the explosion so small? Where did the large core mass end up? Continuing accretion onto the black hole could explain the missing mass. This might occur if the angular momentum of the core was smaller than in the more energetic cases. Other more exotic scenarios, such as merger models, might also work.

A case of a progenitor mass just exceeding the black-hole limit may be that of SN 2002ap. This supernova may not have produced a magnetar and an XRF, because it did not collapse to a neutron star but rather to a black hole[13], yet at the same time the energies involved in the collapse may have been too small to give rise to a GRB.

In our scenario, some soft γ-ray repeaters energized by a magnetar[12,27] may be remnants of GRB 060218-like events. Magnetars could thus generate a GRB at different times. As they are born, when they

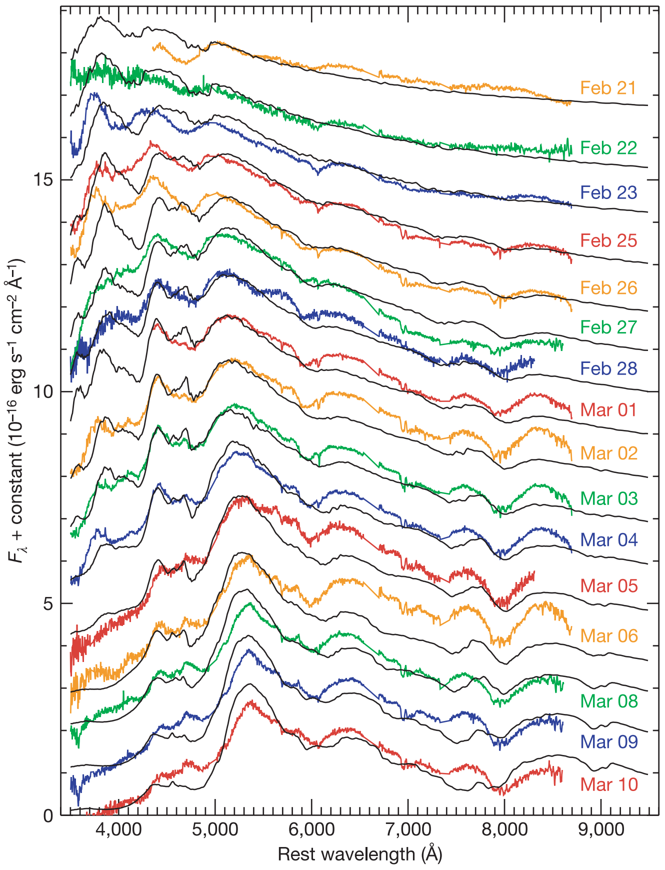

Figure 1 | Spectra of SN 2006aj and synthetic fits. The observed spectra of SN 2006aj (coloured traces) are calibrated in the V band, but elsewhere they may be distorted[9], hence the poorer agreement in some of the red parts. Also, the blue part is not reliable shortward of ~4,200 Å. The synthetic spectra (black traces) were computed using our Monte Carlo spectrum synthesis code[30]. Because of the spectroscopic and photometric similarity to SN 2002ap (ref. 14), we used a similar model of the explosion[13], but to improve the match we reduced the masses of both oxygen and calcium significantly, and decreased $M_{\rm ej}$ and $E_{\rm K}$ accordingly. Our model has $M_{\rm ej} \approx 2 M_\odot$ and $E_{\rm K} \approx 2 \times 10^{51}$ erg. The strongest features in the spectra are due to lines of Fe II, Ti II, and in the later phases Ca II (<4,500 Å), Fe III and Fe II (near 5,000 Å), Si II (near 6,000 Å), O I (near 7,500 Å), and Ca II (near 8,000 Å). The O I and Ca II lines become stronger at more advanced epochs, and are conspicuous because they form at a roughly constant wavelength, corresponding to a velocity (~25,000 km s^{-1}) higher than that of other lines. This indicates the presence of a shell of material, dominated by oxygen, at velocities between about 20,000 and 25,000 km s^{-1}. This high-velocity material may result from the piling up of circumstellar material on the expanding ejecta. We modelled the spectrum by adding a small amount of mass (~$0.10 M_\odot$) at $20{,}000 \lesssim v \lesssim 30{,}000$ km s^{-1}. This results in an increased $E_{\rm K}$ (~2.5×10^{51} erg). That the high-velocity material is mostly oxygen seems to confirm that both the outer supernova ejecta and the stellar wind were dominated by oxygen, and that the progenitor star was an early-type Wolf–Rayet star.

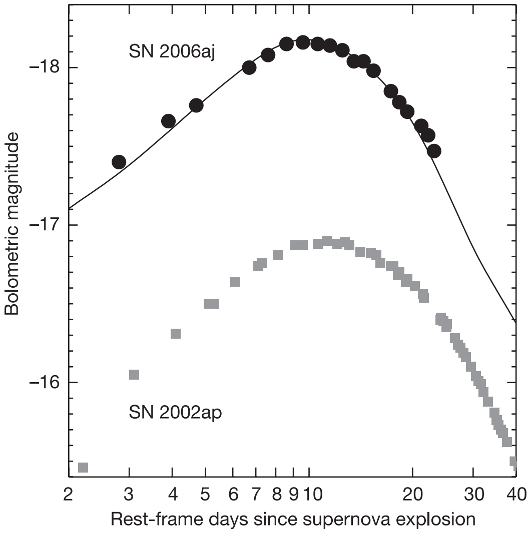

Figure 2 | The light curve of SN 2006aj. The bolometric light curve of SN 2006aj (circles) is compared with the model light curve (solid line), and with the bolometric light curve of SN 2002ap (squares). A supernova light curve is powered by γ-rays released in radioactive decays of freshly synthesized unstable ^{56}Ni to ^{56}Co and hence to stable ^{56}Fe. The γ-rays deposit in the dense ejecta, giving rise to a flux of optical photons. The light curve rises at first as the diffusion time of photons decreases, as the ejecta expand. A maximum is reached when the escaping photon luminosity approximately equals the deposited energy[15]. The light curve then declines as the density becomes low enough to allow significant γ-ray escape. The more massive the supernova ejecta and the smaller their kinetic energy, the more difficult it is for photons to escape, which means that the light curve reaches its maximum later and has a broader peak. The bolometric light curves were constructed by integrating the optical and near-infrared fluxes (for SN 2006aj, optical photometry obtained with the European Southern Observatory's (ESO) Very Large Telescope (VLT) and near-infrared photometry reported in the Gamma-Ray Burst Coordinates Network (GCN) were used), after correcting for the host-galaxy distance/redshift and the reddening towards the supernova—for SN 2006aj, 143 Mpc, $z = 0.0335$, and $E(B - V) = 0.13$ mag (ref. 9). The model light curve is synthesized from the one-dimensional density and chemical abundance structure of the best-fitting spectral models. It corresponds to ~$2 M_\odot$ ejecta expanding with a kinetic energy of ~2×10^{51} erg, having in total ~$0.2 M_\odot$ of ^{56}Ni. The small amount of mass and energy added by the inclusion of the outer oxygen shell (see Fig. 1) have a very limited impact on the light curve because the mass is located at low density and has low optical depth. The explosion of SN 2006aj is assumed to coincide in time with the GRB.

have a very short spin period (~1 ms), an XRF (or a soft GRB) may be produced as in SN 2006aj–GRB 060218. Later (after more than 1,000 years), when their spin rate is much lower, they could produce short-hard GRBs by a giant flare[28]. Finally, if the progenitor star had a massive companion in a close binary system, as may be required for the outer envelope to be stripped and a long-duration GRB or XRF to be produced[26], the system may evolve to a close double-neutron-star system. When the two neutron stars finally merge, a short-hard GRB may again be produced[29].

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

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