The Metamorphosis of Supernova SN 2008D/XRF 080109: A Link Between Supernovae and GRBs/Hypernovae

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The only supernovae (SNe) to show gamma-ray bursts (GRBs) or early x-ray emission thus far are overenergetic, broad-lined type Ic SNe (hypernovae, HNe). Recently, SN 2008D has shown several unusual features: (i) weak x-ray flash (XRF), (ii) an early, narrow optical peak, (iii) disappearance of the broad lines typical of SN Ic HNe, and (iv) development of helium lines as in SNe Ib. Detailed analysis shows that SN 2008D was not a normal supernova: Its explosion energy (E = 6 × 10^44 erg) and ejected mass [=7 times the mass of the Sun (M)] are intermediate between normal SNe Ib and HNe. We conclude that SN 2008D was originally a ~30 M star. When it collapsed, a black hole formed and a weak, mildly relativistic jet was produced, which caused the XRF. SN 2008D is probably among the weakest explosions that produce relativistic jets. Inner engine activity appears to be present whenever massive stars collapse to black holes.

Optical follow-up revealed the presence of a supernova (SN) coincident with the XRF [SN 2008D; RA (2000) = 09 09 30.625; Dec (2000) = +33 08 20.16 (2)]. We detected SN 2008D phot-

Supporting Online Material
www.sciencemag.org/cgi/content/full/321/5893/1183/DC1 SOM Text
Figs. S1 to S5
Tables S1 and S2
References
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The only supernovae (SNe) to show gamma-ray bursts (GRBs) or early x-ray emission thus far are overenergetic, broad-lined type Ic SNe (hypernovae, HNe). Recently, SN 2008D has shown several unusual features: (i) weak x-ray flash (XRF), (ii) an early, narrow optical peak, (iii) disappearance of the broad lines typical of SN Ic HNe, and (iv) development of helium lines as in SNe Ib. Detailed analysis shows that SN 2008D was not a normal supernova: Its explosion energy (E = 6 × 10^44 erg) and ejected mass [=7 times the mass of the Sun (M)] are intermediate between normal SNe Ib and HNe. We conclude that SN 2008D was originally a ~30 M star. When it collapsed, a black hole formed and a weak, mildly relativistic jet was produced, which caused the XRF. SN 2008D is probably among the weakest explosions that produce relativistic jets. Inner engine activity appears to be present whenever massive stars collapse to black holes.

Optical follow-up revealed the presence of a supernova (SN) coincident with the XRF [SN 2008D; RA (2000) = 09 09 30.625; Dec (2000) = +33 08 20.16 (2)]. We detected SN 2008D phot-

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The spectra resembled those of the XRF-SN 2002ap (5, 6) or XRFs (7, 8). The spectra resembled those of the XRF-SN 2006aj (8) or the non-GRB hypernova (HN) SN 2002ap (9) (Fig. 1, top), but a comparison suggests that SN 2008D was highly reddened: We estimate that $E(V - F)_{max} = 0.65$ mag [see supporting online material (SOM)].

The host galaxy of XRF 080109/SN 2008D, NGC 2770 (redshift $z = 0.006494$, distance 31 Mpc), is a spiral galaxy similar to the Milky Way, and highly star-forming ($\sim 0.5$ Mpc), is a spiral galaxy similar to the Milky Way, and highly star-forming ($\sim 0.5$). Accordingly, SN 2008D was classified as a broad-lined SN Ic (Ic−BL) and a moderate star-formation rate, $\sim 0.5$ M$_\odot$/year$^{-1}$ (see SOM). In contrast, typical host galaxies of GRBs are small, compact, somewhat metal-poor, and highly star-forming (10).

In addition to the weak XRF, SN 2008D shows a number of peculiar features, most of which are new. The optical light curve had two peaks (Fig. 2): A first, dim maximum ($V = 18.4$) was reached less than 2 days after the XRF. After a brief decline, the luminosity increased again, reaching principal maximum ($V = 17.37$) ~19 days after the XRF. An 18- to 20-day risetime is typical of GRB-HNe: Normal SNe Ic reach maximum in 10 to 12 days. Few stripped-envelope SNe have very early data, and in GRB-HNe a first peak may be masked by the afterglow. A first narrow optical peak was only seen in the type Ib SN 1999ex (SNe Ib are similar to SNe Ic but show strong helium lines (4)), the type Ib SN 1993J (SNe Ib are similar to SNe Ib but still have some hydrogen), and the type Ic XRF-SN 2006aj). When it was discovered, SN 1999ex was dropping from a phase of high luminosity (11). It reached principal maximum ~20 days later, as did SN 2008D.

Another unusual feature is the spectral morphism (Fig. 3). Unlike SNe 2006aj and 2002ap, the broad absorptions did not persist. As they disappeared, He I lines developed (12). By principal maximum, SN 2008D had a narrow-lined, type Ib spectrum (Fig. 1, bottom).

Broad lines require material moving with velocity $v > 0.1c$, where $c$ is the speed of light (13). Their disappearance implies that the mass moving at high velocities was small.

Late development of He I lines, previously seen only in SN 2005bf (14), is predicted by theory (15). Helium levels have high excitation potentials, exceeding the energy of thermal photons and electrons. Excitation can be provided by the fast particles produced as the $γ$-rays emitted in the decay chain of $^{56}$Ni thermalize (16). This is the process that makes SNe shine. In the first few days after explosion, thermalization is efficient because of the high densities and because not enough particles are available to excite helium. Only when density drops sufficiently can more particles escape the $^{56}$Ni zone and excite helium.

We reproduced the spectral evolution and the light curve of SN 2008D after the first peak, using a model with $M_\Delta \sim 7 M_\odot$ and spherically symmetric $E \sim 6 \times 10^{51}$ erg, of which $\sim 0.03 M_\odot$, with energy $\sim 5 \times 10^{50}$ erg, are at $v > 0.1c$ (Figs. 1 and 2 and SOM). Our light curve fits indicate that SN 2008D synthesized $\sim 0.09 M_\odot$ of $^{56}$Ni, like the non-GRB HN SN Ib 2002ap (9) and the normal SN Ic 1994I (17) but much less than the luminous GRB-HN SN 1998bw (6). The rapid rise in luminosity after the first peak requires that some $^{56}$Ni (0.02 $M_\odot$) was mixed uniformly at all velocities $> 9000$ km s$^{-1}$. This is a typical feature of HNe and suggests an aspherical explosion (18). Asphericity may affect our estimate of the energy, but not the $^{56}$Ni mass (19).

Comparing the mass of the exploding He star that we derived with evolutionary models of massive stars, we find that the progenitor had main sequence mass $\sim 30 M_\odot$. A star of this mass is likely to collapse to a black hole, as do GRB-SNe (20). So, SN 2008D shared several features of GRB/HNe. However, all SNe with GRBs or strong XRFs initially had velocities higher than SN 2008D or SN 2002ap (fig. S3) and never showed helium. Had the He layer not been present in SN 2008D, the explosion energy would have accelerated the inner core to higher velocities, and broad lines may have survived.

The characterizing features of SN 2008D (weak XRF, first narrow optical peak, initially broad-lined SN Ic spectrum that later transformed into a narrow-lined SN Ib spectrum) may be common to all SNe Ib, or at least a substantial fraction of them, and perhaps some SNe Ic (which, however, contain little or no helium). The light curves of various SNe Ib are rather similar (21). The first peak was observed only for SN 1999ex, but lack of x-ray monitoring probably prevented the detection of more weak XRFs and the early discovery of the associated SNe. On the other hand, SN 2008D (and possibly most SNe Ib) was more energetic than normal core-collapse SNe, including most SNe Ic.

Type II SNe in late spiral/irregular galaxies (the typical Hubble type of GRB hosts) are about 6 times as frequent as SNe Ib (22). Although the serendipitous discovery of an SN Ib by XRT may be a statistical fluctuation, it may also suggest that the soft x-ray emission accompanying SN 2008D is typical of overenergetic SNe Ib and absent (or very weak) in normal core-collapse SNe.

The x-ray spectrum of SN 2008D (in total ~500 photons) can be fitted with either a simple
3.8 × 10^6 K) and a power law. In the latter case, the model of the explosion kinetic energy (28). All known SNe Ic with a broad light curve curve of SN 1999ex, which is similar to that of SN 2008D, was fitted reasonably well by a He-star explosion model with M_{ej} = 5 M_\odot and E \sim 3 \times 10^{51} \text{erg} (12). Such a model would also match the light curve of SN 2008D, but it probably would not reproduce the broad lines that characterize the early spectra. This would require a model containing some high-velocity material, leading to a larger E without noticeably affecting the value of M_{ej} or the light curve shape. The line shows a synthetic bolometric light curve computed with a Monte Carlo code (30) for a model with M_{ej} = 7 M_\odot and E \sim 6 \times 10^{51} \text{erg}. The model does not address the physics that may be responsible for the first narrow light curve peak, but only the main peak, which is due to diffusion of radiation in the SN envelope following the deposition of \gamma-rays and positrons emitted in the decay chain 54Ni to 56Co and 56Fe.

power law indicating a nonthermal emission mechanism or a combination of a hot black body (T = 3.8 \times 10^9 \text{K}) and a power law. In the latter case, the unabsorbed luminosity of the black-body component is a small fraction of the total x-ray luminosity. The high temperature and low luminosity (L = 1.1 \times 10^{43} \text{erg \ s}^{-1}) of the black-body component at first peak (~100 s after the onset of the XRF) imply an emitting radius R_{ph} \sim 10^{10} \text{cm} (see SOM, Section 4). This is at least one order of magnitude smaller than the size of Wolf-Rayet stars, the likely progenitors of SNe Ibc.

The x-ray flare and the first optical peak are most likely associated (23). The time scale of the first optical peak may suggest that it was related to shock breakout. A signature of shock breakout is a hot black-body x-ray spectrum immediately after the explosion. Thermal x-ray emission was suggested for SN 2006aj (24), whereas no x-ray data are available for SN 1999ex. The model of (23) uses a spherical configuration and a black-

body component at ~0.1 keV, below the XRT energy range. This yields a large radius, which the authors explain by invoking the presence of a dense surrounding medium that bulk-Comptonizes the shock breakout emission to higher energies, producing the power-law spectrum observed by XRT between 0.3 and 10 keV.

On the other hand, the angular size of an emitting area with radius R_{em} \sim 10^{10} \text{cm} is typical of GRB jets. This leads naturally to an alternative scenario, which we propose here: XRF 080109 was the breakout of a failed relativistic jet powered by a central engine, as in GRBs. The jet failed because its energy was initially low or because it was damped by the He layer, which is absent in GRB-HNe, or both. The presence of a jet is supported by our conclusions that SN 2008D was highly energetic and that a black hole was probably formed when the star collapsed. The marginal breakout of the jet produced thermal x-rays and relativistic particles that caused the power-law x-ray component. It also caused the first optical peak. The time scale of the first peak and the x-ray flare and the corresponding radii and temperature are consistent with emission from rapidly expanding, adiabatically cooling material. The weakness of the jet resulted in the low x-ray flux and the small amount of material with \nu > 0.1c. The failed jet contributed anisotropically to the SN kinetic energy. Lateral spreading of the ejecta with \nu > 0.1c leads to an angular size larger than the x-ray-emitting region, which is needed to produce the observed broad lines. The small amount of high-velocity material moving along our line of sight may also indicate that we viewed the explosion considerably off-axis. This can be tested by polarization or line profile studies at late times, as in SN 2003jd (25). The jet will spread further after breakout, and it could dominate the radio emission at later times.

The scenario we propose implies that GRB-like inner engine activity exists in all black-hole–forming SNe Ibc (26). SN 2008D (and probably other SNe Ib) has significantly higher energy than normal core-collapse SNe, although less than GRB/HNe. Therefore, it is unlikely that all SNe Ibc, and even more so all core-collapse SNe, produce a weak x-ray flash similar to XRF 080109. The presence of high-energy emission (GRB or XRF) depends on the jet energy and the stellar properties. Only massive, energetic, stripped SNe Ic (HNe) have shown GRBs. In borderlinen events like SN 2008D, only a weak, mildly relativistic jet may emerge, because the collapsing mass is too small and a He layer damps the jet. For even less massive stars that still collapse to a black hole, producing a less energetic explosion (e.g., SN 2002ap), no jet may emerge at all. Stars that only collapse to a neutron star are not expected to have jets unless the neutron star is rapidly spinning (27). SN 2008D thus links events that are physically related but have different observational properties.

References
Hydrodefluorination of Perfluoroalkyl Groups Using Silylcarborane Catalysts

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Carbon-fluorine bonds are among the most unreactive functionalities in chemistry. Interest in their activation arises in part from the high global warming potentials of anthropogenic polyfluororganic compounds. Conversion to carbon-hydrogen bonds (hydrodefluorination) is the simplest modification of carbon-fluorine bonds, but efficient catalytic hydrodefluorination of perfluoroalkyl groups has been an unmet challenge. We report a class of carborane-supported, highly electrophilic silyl compounds that act as long-lived catalysts for hydrodefluorination of trifluoromethyl and nonafluorobutyl groups by widely accessible silanes under mild conditions. The reactions are completely selective for aliphatic carbon-fluorine bonds in preference to aromatic carbon-fluorine bonds.

Carbon-fluorine bonds are among the most passive functionalities in chemistry (1), and their selective activation and transformation under mild conditions remains a poorly realized challenge (2–5). The thermodynamic issues are considerable: C-F is the strongest single bond to carbon (1–3). The thermodynamic obstacles are compounded by the kinetic issues: Organic fluorides are poor ligands or Lewis bases, and poor substrates for nucleophile substitution or oxidative addition to metals (1–4). In all of these regards, compounds containing fully fluorinated perfluoroalkyl groups prove even more inert than compounds containing a single C-F bond. With the increasing degree of fluorination at carbon, the strength of the C-F bond increases, and the C-F bond distances decrease, resulting in substantial steric shielding of the carbon site (3).

Perfluoroalkyl-containing organic compounds have beneficial uses in technology. Some applications include blood substitutes fostered by high O2 solubility and inertness (1, 6) as well as solvent media for biphasic synthesis and purification (fostered by low miscibility with water and hydrocarbons) (6). On the other hand, perfluoroalkanesulfonic acid derivatives (PFOS), used in surfactants and in fluorinated polymer production, have been recently shown to be toxic, widely spread in the biota, and highly persistent (7). Perfluoroalkyl-containing chlorofluorocarbons (freons or CFC), hydrofluorocarbons (partially fluorinated alkanes, HFC) and perfluorocarbons (perfluoroalkanes, PFC) are of increasing concern as anthropogenic “super-greenhouse gases” (8) of high global warming potential and exceedingly high atmospheric lifetimes. Development of efficient and economical chemical strategies for their disposal is thus of vital importance.

Transition-metal–mediated C-F activation has received substantial attention (2–5). The approach typically employs highly reducing, electron-rich metal reagents or catalysts. The critical cleavage of the C-F bond in this case is by definition of reductive nature, either through an oxidative addition or a single-electron transfer step. The simplest modification of the C-F bond is its conversion to the simplest functional group: a C-H bond (hydrodefluorination or HDF). The scope of the transition metal–catalyzed HDF has been largely limited to fluoroarenes (2–5). HDF of poly(tetrafluoroethylene) by stoichiometric Li metal in ammonia has been reported (9). Conversion of a C-F to a C-C bond is also of interest, but the progress so far has been limited (10). Recently, a Nb-mediated activation of trifluoromethylarene substrates with concomitant conversion of C-F bonds to C-H and C-C bonds was reported (11).

We were attracted to a conceptually different approach to C-F activation, in which the key C-F cleavage proceeds by a Lewis acid abstraction of fluoride rather than a redox event (Fig. 1A). Conventional acids, such as SiO2 or concentrated H2SO4, require very high temperatures for cleavage of C-F bonds in perfluoroalkyl groups (12, 13). In 2005, we reported an implementation of the nonredox approach under ambient conditions by using a silylum (R3Si+) Lewis acid (14). The proposed mechanism is depicted in Fig. 1A. Abstraction of fluoride by silylum from a C-F bond is complemented by the abstraction of hydride by the resultant carbocation from an Si-H bond. The overall process can be viewed as a Si-H/C-F metathesis (with conversion to Si-F/C-H). Given that Si-F is a stronger bond than C-F, and C-H is a stronger bond than Si-H, this metathesis is a very

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![Fig. 1](https://www.sciencemag.org/content/full/1158088/DC1/fig1.png)

Fig. 1. (A) Representation of different approaches to C-F bond cleavage. X stands for an organic substituent, and the X2 notation does not imply that the three substituents must be identical. (B) The stoichiometry of Si-mediated HDF and the proposed mechanism.