**SUPERNOVAE**

A type Ia supernova at the heart of superluminous transient SN 2006gy

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Superluminous supernovae radiate up to 100 times more energy than normal supernovae. The origin of this energy and the nature of the stellar progenitors of these transients are poorly understood. We identify neutral iron lines in the spectrum of one such supernova, SN 2006gy, and show that they require a large mass of iron (≥0.3 solar masses) expanding at 1500 kilometers per second. By modeling a standard type Ia supernova hitting a shell of circumstellar material, we produce a light curve and late-time iron-dominated spectrum that match the observations of SN 2006gy. In such a scenario, common envelope evolution of a progenitor binary system can synchronize envelope ejection and supernova explosion and may explain these bright transients.

Superluminous supernovae (SNe) are a rare type of astrophysical explosion that emit large amounts of energy, more than can be explained by standard supernova powering mechanisms. One of the first to be observed was SN 2006gy, which showed narrow hydrogen lines (supernova type IIn) indicating interaction with a circumstellar medium (CSM). SN 2006gy radiated about 10³¹ erg in a few months (1, 2). Proposed mechanisms to produce such a transient include large amounts of radioactivity in a pair-instability supernova (PISN) (1), a collision between a core-collapse supernova (CCSN) and a Luminous Blue Variable–like eruption (3), and a pulsational pair-instability explosion (4). However, the nature of SN 2006gy remains unclear and disputed.

A spectrum of the supernova at 394 days after explosion (5) revealed a set of emission lines around 8000 Å that could not be identified. Figure 1 shows this spectrum, after removal of light echoes (light from earlier epochs reflected by circumstellar dust) (6). By searching atomic line lists, we determined that these lines all coincide with low-excitation, strong transitions in Fe I (6).

These lines are predicted by emission line models for slow-expanding supernova ejecta (7). They arise from the Z''D multiplet of Fe I at 2.4 eV above the ground state, which is excited by thermal electron collisions at typical supernova temperatures of a few thousand kelvin. Most supernovae have, however, too little neutral iron and expansion velocities that are too high to exhibit these lines in their spectrum. In addition to these Fe I lines, the spectrum of SN 2006gy shows lines from Ca II and Fe II and is thus dominated by heavy elements, likely produced in explosive oxygen and silicon fusion. The FWHM (full-width-at-half-maximum) of these iron and calcium lines is ~1500 km s⁻¹, which corresponds to the characteristic expansion velocity of the gas at +394 days.

To obtain constraints on the iron producing this emission, we calculated a grid of iron line (Fe I and Fe II) emission models with the spectral synthesis code SUMO (8), varying the iron mass, temperature, ionization, and clumping (degree of compression compared to a uniform distribution) (6). Small masses of iron (≤0.1 solar masses (M☉)) cannot produce the observed luminosity for any physical conditions (Fig. 2). To both fulfill ionization balance and reproduce the observed emission ratio between Fe I and Fe II lines, another constraint M(Fe) ≥ 0.3 M☉ can be derived, assuming a filling factor (the inverse of clumping) of 0.1 to 1 (6). Lower masses lead to an ionization state that is too high, producing emission mainly from Fe II and Fe III, rather than Fe I. The iron mass

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**Fig. 1.** Observed spectrum of SN 2006gy at +394 days (red) compared to a standard type Ia model (W7) with hydrodynamic velocities reduced by a factor of 7 (blue). The model also has 3 M☉ of CSM mixed with the la ejecta. The black dashed line around 6560 Å shows the upper limit on Hα emission from the supernova. The inset shows an enlarged area on the lines at 7900 to 8500 Å that we identify as due to Fe I. The black line shows a theoretical model of emission from 0.5 M☉ of Fe at 5000 K, scaled to the same distance as SN 2006gy.
limit holds also under exploration of smaller filling factors (6). A large mass of iron is therefore inferred, likely arising from radioactive decay of $^{56}$Ni (through the intermediary $^{56}$Co), the main product of explosive silicon fusion.

At +394 days after explosion, SN 2006gy was about 100 times fainter compared with previous observations at +200 days. A fundamental property of a localized CSM is that the shock will traverse the CSM on a time scale of 230 days ($R/10^{16}$ cm)/(v$_{\text{shock}}$/5000 km s$^{-1}$), where $R$ is the radius and v$_{\text{shock}}$ is the shock speed. Similar drops in brightness have been seen in other luminous type IIn supernovae (9, 10). In its second and third year after explosion, SN 2006gy became dominated by an echo with slower decay than either interaction or radioactively powering (II).

The amount of initial radioactive $^{56}$Ni needed to match the estimated luminosity of the supernova at +394 days is 0.5 $M_\odot$ (6). Figure 1 (inset) shows a theoretical emission spectrum of 0.5 $M_\odot$ of Fe I at 5000 K, scaled to the same distance as SN 2006gy, which reproduces the observed Fe I lines. These strong iron lines in SN 2006gy are difficult to reconcile with several previously suggested models in which there is no $^{56}$Ni production, such as the collisions of pulsational pair instability shells (4).

Core-collapse supernovae (arising when the core of a massive star collapses to a neutron star or black hole) produce much less $^{56}$Ni, typically 0.1 $M_\odot$ (12, 13), although a small fraction, almost all in the broad-lined type Ic class, has inferred $^{56}$Ni masses $\gtrsim$ 0.3 $M_\odot$ (14). Such an engine for SN 2006gy can, however, be excluded on two grounds. First, for a CCSN to produce 0.5 $M_\odot$ of $^{56}$Ni, the explosion energy must exceed $10^{43}$ erg (15). Because wind-driven mass loss and pair-instability pulsations limit the final mass of the supernova progenitor to about 10 solar masses, these supernovae expand fast (6000 to 12,000 km s$^{-1}$), as confirmed by late-time spectroscopic observations (14). For such a supernova to reach a velocity of 1500 km s$^{-1}$ after a few hundred days, the ejecta must have been strongly decelerated by a massive CSM, with associated re-radiation of the bulk of the original kinetic energy ($\sim 10^{52}$ erg). The observed radiated energy in SN 2006gy is an order-of-magnitude lower at $10^{51}$ erg (6), preventing any self-consistent CCSN scenario. Second, CCSN ejecta are dominated by oxygen, with strong [O I] lines after a few hundred days, of which SN 2006gy shows none.

Two model scenarios can explain $^{56}$Ni mass of 0.5 $M_\odot$ expanding with 1500 km s$^{-1}$ at 400 days: a pair-instability explosion of a $\sim 90$ $M_\odot$ He core (16); or a type Ia supernova [the thermonuclear explosion of a white dwarf (WD)] decelerated by strong circumstellar interaction. The ejecta mass needed to trap gamma rays from radioactive decay (which transfer the decay energy to heat) at 400 days is 1.8 $M_\odot$ (setting the optical depth $\tau_e = \kappa_e \rho R = 1$, where $\kappa_e$ is the gamma-ray opacity and $\rho$ is the density), and the gamma rays therefore mainly power the supernova ejecta rather than the CSM in both cases.

We calculated model spectra for the two model scenarios with SUMO and found good agreement for both, as they have similar core structures. Figure 1 shows spectra calculated by using the type Ia explosion model W7 (17, 18), with all velocities in the hydrodynamic model reduced by a factor of 7 to mimic the slowdown due to CSM interaction (leading to higher densities at any given time). We mixed the ejecta with a few solar masses of CSM material; however, the spectrum was not sensitive to this (6).

This W7+CSM model reproduces the Fe I lines, the [Ca II] 7291, 7323 Å doublet, and the only ionized iron line seen, [Fe II] 7155 Å. The Ca II triplet at 8500 to 8700 Å is underproduced, possibly because the Ca-rich region is not compact enough; higher density favors a stronger calcium triplet.

The degeneracy between type Ia and PISN models in this late (nuclear) phase can be broken by considering the earlier phases of the supernova. We calculated the total amount of light emitted by SN 2006gy using all the spectral and photometric data available in the literature (1, 19, 20). We obtain $9 \times 10^{50}$ erg, close to that expected in the strong interaction limit of a type Ia supernova where a large fraction of the kinetic energy of (1 to 2) $\times 10^{51}$ erg is converted to radiation (6). Some previous estimates of this number were a factor of 2 to 3 higher, but were based either on single-band data with an assumed bolometric correction (I), or extrapolated blackbodies with high ultraviolet(UV)/blue flux (20). Such UV/ blue emission is often blocked by line opacity in supernovae, and the spectra of SN 2006gy show such behavior (6). We used the radiation hydrodynamic code SNEC (21) to calculate light curves arising when a standard Ia SN ejecta (W7), or PISN ejecta, collide with a dense H-rich CSM. The resulting light curves for the
Fig. 3. Type Ia-CSM light-curve models compared to SN 2006gy (red points). (A) Bolometric luminosity (emission integrated over all frequencies) and (B) velocity of the Ia ejecta (at $M = 0.5 M_\odot$). This iron only becomes observable in the nebular phase spectrum at +394 days after explosion (= +324 days after peak). All models have outer CSM radius $R_{\text{CSM}} = 8 \times 10^{15}$ cm. The green curve is representative of models with too small CSM mass ($\lesssim 5 M_\odot$); the light curve peak is too narrow and too bright, and the deceleration is insufficient. The blue curve is representative of models with too much CSM ($\gtrsim 25 M_\odot$); the CSM interaction powers the light curve for too long and the slowdown is too severe. The black model represents a case of CSM mass ($13 M_\odot$) where all properties are reproduced.

Ia case match SN 2006gy if a CSM mass of about 10 $M_\odot$ is present (Fig. 3). Pair-instability supernovae, by contrast, produce light curves that are in strong disagreement with observations (fig. S6).

Inspection of the Ia-CSM hydrodynamic models shows that the ejecta are decelerated to 1500 km s$^{-1}$ following interaction with a CSM with properties suitable for reproducing the light curve (Fig. 3). This matches the observed velocities of the Fe I lines at +394 days. The type Ia explosion energy, $1.3 \times 10^{51}$ erg for the standard scenario (18), is accounted for by about $3 \times 10^{50}$ erg still in kinetic energy at +394 days ($\sim 15 M_\odot$ at 1500 km s$^{-1}$, both ejecta and CSM expand with this asymptotic velocity), with the rest radiated. The “type Ia-CSM” hypothesis thus matches all observations. This scenario has been previously proposed for SN 2006gy (2) but was then largely forgotten, as most analyses focused on massive-star progenitors.

From the CSM extension and velocity, the CSM material must have been ejected between 10 and 200 years before the supernova explosion. A candidate scenario to explain this is common envelope evolution of a binary progenitor system, in which a white dwarf spirals into a giant or supergiant companion star. This could causally link the processes of envelope ejection and a merger with the core of the other star, producing the explosion. Such synchronization by common envelope evolution has previously been discussed in other contexts (22). The inspiral process has been shown to robustly transfer energy and angular momentum from the orbit to the common envelope, and eject most or all of this, while the orbital separation shrinks by a factor 100 or more (23, 24).

The ejection time scale in SN 2006gy matches the time scales for common envelope ejection obtained in simulations: ~10 years for red giants engulfing WDs (23), and 2 to 200 years for more-massive red supergiants (RSGs) (24). The released orbital energy for a WD of mass $M_{\text{WD}}$ spiralling in toward a companion with core mass $M_{\text{core}}$ and radius $R_{\text{core}}$ is

$$4 \times 10^{48} \frac{M_{\text{core}}}{M_\odot} \frac{M_{\text{WD}}}{M_\odot} \left(\frac{R}{R_\odot}\right)^{-1} \text{ erg}$$

where $R_\odot$ is the solar radius. This is sufficient to unbind 10 $M_\odot$ of envelope material in an extended star (binding energy $4 \times 10^{48}$ erg for a typical $R = 100 R_\odot$) and also account for the kinetic energy of the ejected envelope ($10^{48}$ erg for 100 km s$^{-1}$). It is less clear how the two cores merge and explode. These steps are rarely explored in inspiral simulations, because of computational difficulties, although some results have shown that less-evolved giants merge more easily (26). Material may also form a disk around the two cores that could drive the final stages of merging (25).

A similar scenario may explain type IIa supernovae, a rare class that have spectra of type Ia at early times but later transition to type IIn (but much less luminous than SN 2006gy). One suggestion put forth is the common envelope ejection in a merger of a WD and an Asymptotic Giant Branch (AGB) star (26). Such a scenario has been criticized on the grounds that the final merger would have to occur by gravitational waves, which would take much longer than decades or centuries (27). However, the last stages of common envelope evolution are not well understood, so that conclusion may be premature.

It is possible that SN 2006gy is an extreme example of the Ia-CSM family, with higher CSM mass located closer to the supernova compared to other cases. This would be more efficient at converting kinetic energy to radiation, over a shorter time scale, leading to the extreme luminosity. It also led to strong ejecta deceleration that trapped gamma rays and produced the distinct narrow Fe lines after a few hundred days. Type IIa supernovae show longer-lasting interactions with a more extended CSM, which would not slow the expanding core sufficiently to produce a distinct signature from the inner ejecta at late times.

Other superluminous type IIn SNe such as SN 2006tf (28), SN 2008fz (29), and SN 2008am (30) share several similarities with SN 2006gy. The total radiated energy in these events is also around $10^{53}$ erg, so some may also represent a type Ia SN exploding in a massive common envelope–ejected CSM. These other supernovae were, however, much farther away, with no observable signature similar to the +394-day spectrum of SN 2006gy; attempts at late-time observations yielded either no detections or still-ongoing interaction through broad hydrogen lines (28–30).

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplementary Text
Figs. S1 to S11
Tables S1 and S2
References (32–66)