Superluminous supernova SN 2006gy as a result of common envelope merger between a white dwarf and a massive star

Jerkstrand, Maeda and Kawabata, Science 2020, Vol. 367, 6476

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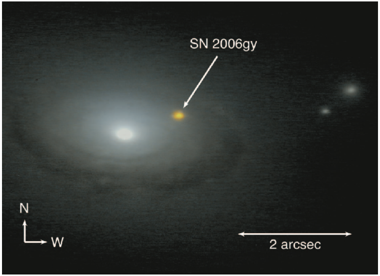

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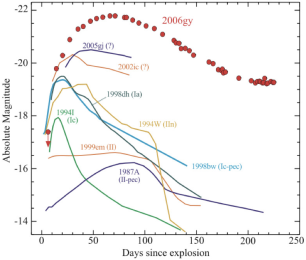
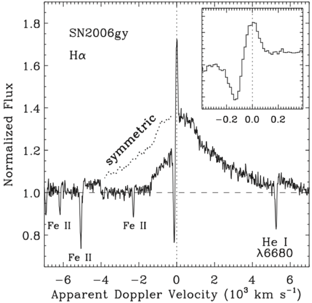
SN 2006gy - one of the brightest SNe ever seen

Smith 2007,2008,2010, Ofek 2008, Agnoletto 2009, Miller 2010, Fox 2015, +more

- Type **IIn**.
- Rise time **70d**, peak mag **-22**, radiated energy $\sim \mathbf{10^{51}}$ erg. Significant extinction ($E_{B-V} = 0.5 - 0.75$).
- **Interaction with a massive ($\sim 10\ M_\odot$), slow-moving ($\sim$ 100 km/s) CSM** indicated from narrow H lines. This CSM **ejected $\lesssim$ 100y before the SN**.
- A diverse set of models proposed: e.g. *pulsational pair instability SN, an LBV core-collapse soon after a Eta-Carina like eruption,...*





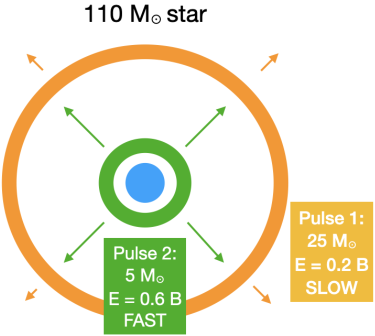
A pulsational PISN?

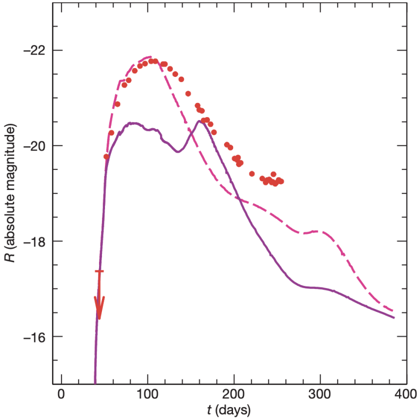
nature   Vol 450 | 15 November 2007 | doi:10.1038/nature06333

LETTERS

Pulsational pair instability as an explanation for the most luminous supernovae

S. E. Woosley[1], S. Blinnikov[1,2,3] & Alexander Heger[1,4]





Ia-CSM? An early idea that was then forgotten

arXiv > astro-ph > arXiv:astro-ph/0612408v1

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[Submitted on 14 Dec 2006 (this version), latest version 7 Feb 2007 (v2)]

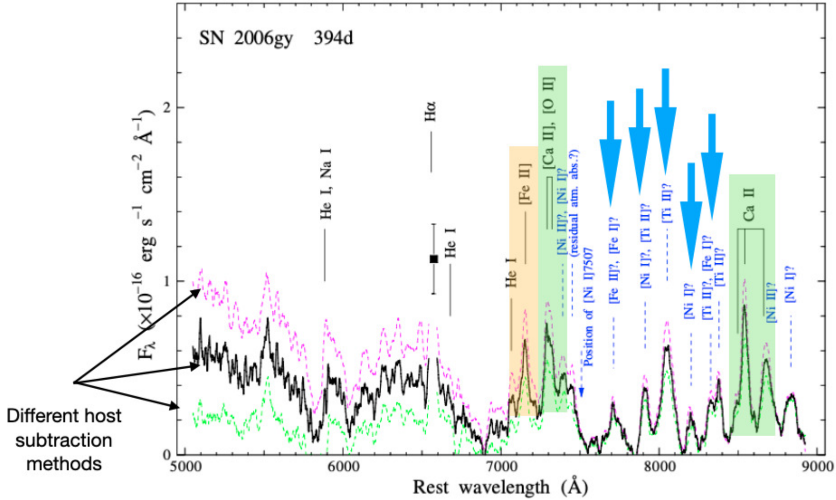
SN 2006gy: An extremely luminous supernova in the early-type galaxy NGC 1260

E. O. Ofek, P. B. Cameron, M. M. Kasliwal, A. Gal-Yam, A. Rau, S. R. Kulkarni, D. A. Frail, P. Chandra, S. B. Cenko, A. M. Soderberg, S. Immler

With an extinction-corrected V-band peak absolute magnitude of about -22.2, supernova (SN) 2006gy is probably the brightest SN ever observed. We report on multi-wavelength observations of this SN and its environment. The optical spectra and the slow light-curve evolution resemble those of members of the hybrid IIn/Ia SN class, also called type-IIa SNe. The total radiated energy in the first two months is about 1.2 x 10^51 erg, comparable to the total mechanical energy release of a type-Ia SN. If the engine behind SN2006gy is a type-Ia SN, the rapid conversion of mechanical energy to radiation requires a very dense circumstellar medium, which in turns implies an extreme mass loss rate for the progenitor, ~10^-2 solar mass per year over a period of ~100 yr prior to explosion. Such a mass-loss rate is a challenging requirement for most proposed models of type-IIa SN. Unlike the four previously known type-IIa SNe, the host galaxy NGC 1260 is not a star-forming galaxy, but rather an S0 galaxy dominated by an old stellar population, which probably has a relatively high metallicity. However, our high resolution adaptive optics images reveal a dust lane in this galaxy, passing about 300 pc (projected) from the SN position. These observations add more questions as to the origin of the enigmatic IIa supernovae.

Strange, unidentified emission lines seen at +394d

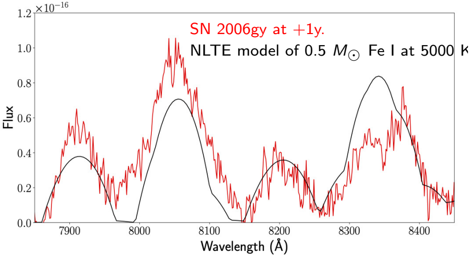
Kawabata et al 2009 Ca and Fe only other lines seen.

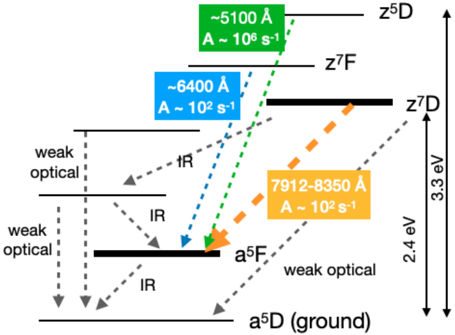


- Line widths → 1500 km s^{-1} expansion.

Identification (10y later) : Fe I *Jerkstrand, Maeda & Kawabata 2020*

These lines have not been seen before in any SN.



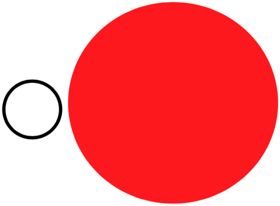


Modelling of the lines constrains the iron mass to $\boxed{0.3 < M_{Fe} < 2.1\ M_\odot}$.
Also, the brightness of the spectrum at +1y matches the decay of 0.5 $M_\odot$ ^{56}Ni.

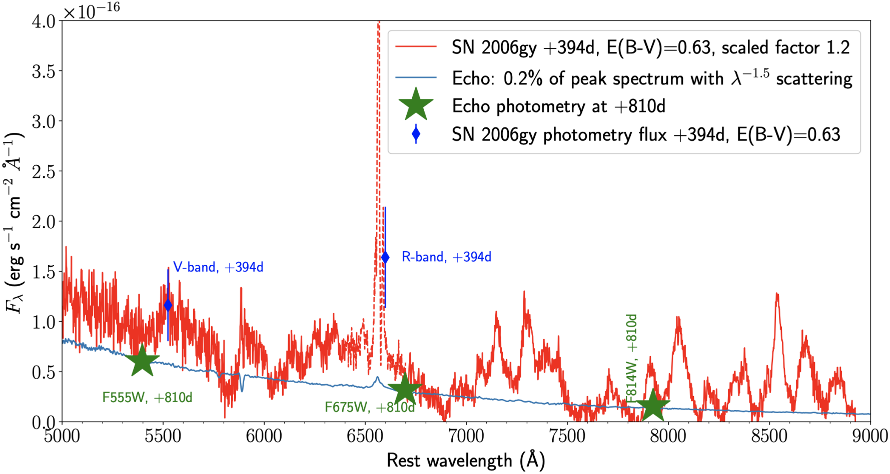
- **Pulsational PISN?** No. These have $M_{^{56}\mathrm{Ni}} = 0$.
- **Core-collapse SN?** Nja... These have $M_{^{56}\mathrm{Ni}} \lesssim 0.2\ M_\odot$. Also no O lines seen in SN 2006gy.

Back to Ofek's idea..*could SN 2006gy be the results of a white dwarf merging with a massive star, ejecting a common envelope, and then exploding as a Ia SN?*

- ✓ **Type Ia SNe make the right amount of ^{56}Ni** $(0.3 - 0.7\ M_{\odot})$.
- ✓ **Causally connects the CSM ejection with the SN explosion** $\rightarrow$ *only model scenario that can account for the inferred <100y synchronization*.
- ✓ **Efficient CE ejection when compact objects spirals into RG/RSG envelopes has been demonstrated** - timescales of years/decades.

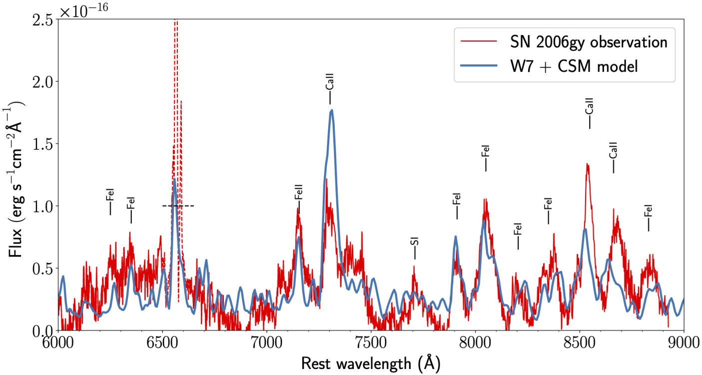


Preparing for model comparisons : detailed data reduction



Testing the idea: Spectrum of a decelerated Ia SN at +1y fits reasonably well.

Spectral simulations with the SUMO NLTE code. W7 ejecta model with scaled down velocities (factor 7), with a few solar masses CSM mixed in.

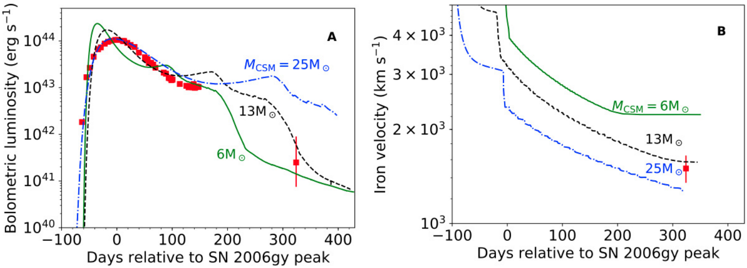


- ✓ Fe I lines emerge.
- ✓ No flux rescaling - a major strength of the model.
- ✓ Physical conditions (temperature, ionization) satisfactory.

Testing the idea: The light curve properties also work out

SNEC with a 2-parameter CSM (M_{CSM},R_{CSM}).

The CSM mass controls both light curve duration and iron deceleration.



- Too large CSM masses give interaction for too long and decelerates the iron too much.
- Too small CSM masses give too fast rise and too bright peak, and insufficient iron deceleration.
- A $\sim$ $10 - 15\ M_\odot$ CSM gives the right properties.

Questions raised if WD-RG/RSG merger is the right explanation

1. How do you get a WD close to a RG or RSG star?
2. How do you get it to spiral in, eject virtually all the envelope, and merge with the core of the other star?
3. How do you get it to explode?

Support in the binary stellar evolution and CE literature for (1) and (2), e.g. Tutokov 1993, Tauris & Sennels 2000, Terman+1994,1995, Sandquist+1998, Ablimit 2021.

Little known about (3) - major differences if companion is AGB star (WD core) or RSG (He core).

Ia-CSM? An early idea that was then forgotten

SUPERNOVA: THE RESULT OF THE DEATH SPIRAL OF A WHITE DWARF INTO A RED GIANT

WARREN M. SPARKS AND THEODORE P. STECHER
Goddard Space Flight Center, Greenbelt, Maryland
Received 1973 June 18; revised 1973 September 13

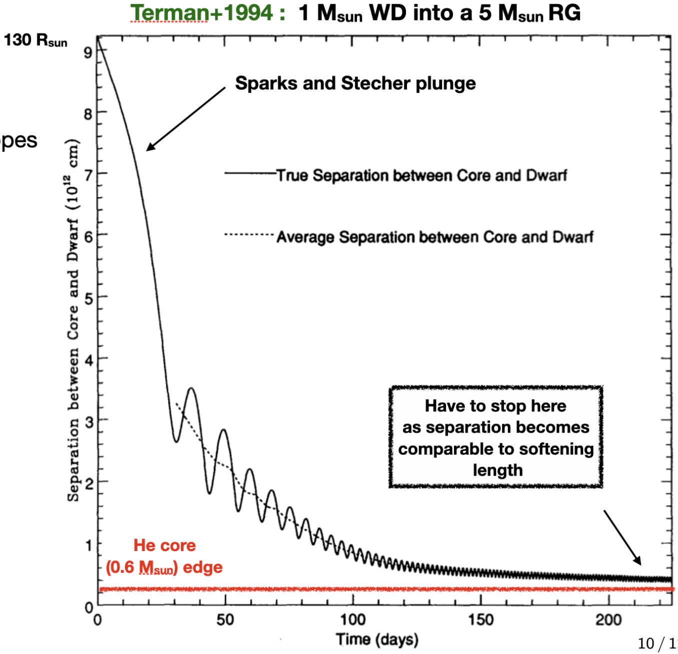
ABSTRACT

The proposed model is a binary consisting of a white dwarf and a star evolving toward the red-giant branch. Conditions are given under which the revolution period of the binary and the rotation period of the red giant will reach a synchronous state and under which no stable synchronous orbit is possible. For the case of a nonstable synchronous orbit, the evolution of the decay of the orbit is given. It is shown that the white dwarf spirals in toward the red giant, enters the red giant's surface, and drops rapidly toward the core. We suggest that a supernova explosion will result from a collision with the core and leave a neutron stellar remnant. The relationship to binary X-ray stars is discussed.

Ia-CSM? An early idea that was then forgotten

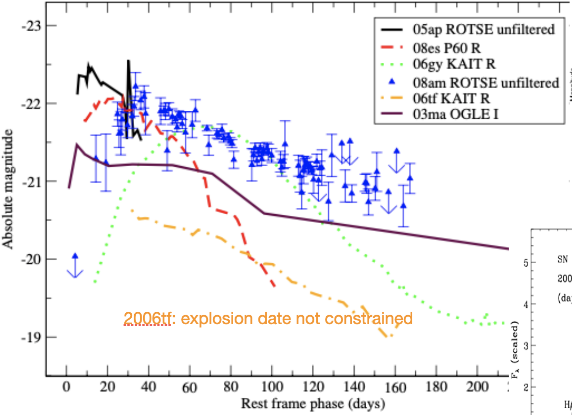
Simulations predict ejection of whole envelopes on time-scales 1-10y.

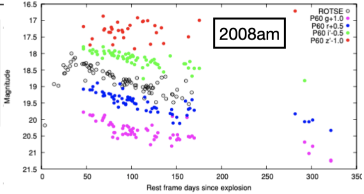
e.g. Terman+1995, Yorke+1995, Sandquist 1998, Taam and Sandquist 2000

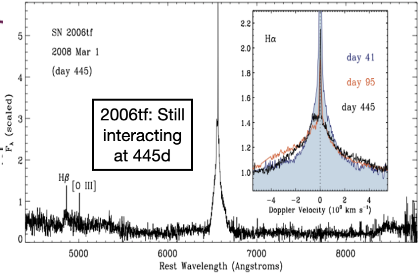


Others?

SN 2008am, 2006tf, 2008fz, 2008es..
All at >~ 1 Gpc (2006gy was at 75 Mpc) so same kind of data campaign more difficult.





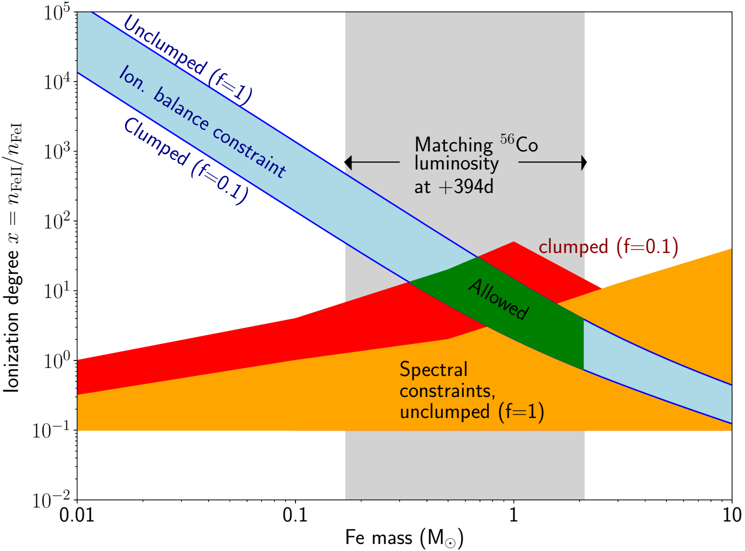


Summary

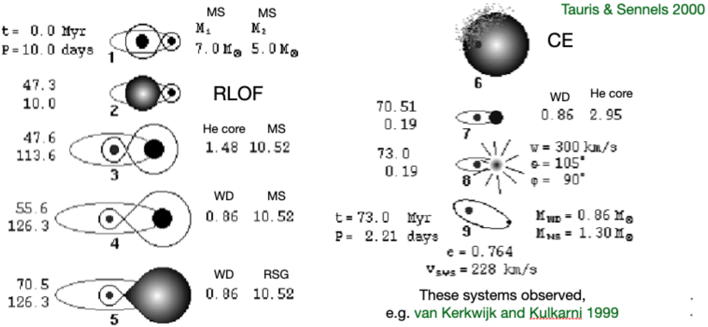
- **A large iron reservoir** ($\sim 0.5\ M_\odot$) identified in the superluminous Type IIn supernova SN 2006gy, almost certainly coming from ^{56}Ni. This rules out several previous scenarios such as shell collisions (these are ^{56}Ni-free).
- A model scenario of a **white dwarf merging with a massive companion and then exploding into the ejected CE** can reproduce both light curve and spectra well : only scenario that explains why a SN occurs soon after (< 100y) a massive CSM creation.
- Best-fitting CSM mass is 10-15 $M_\odot$ which would suggest a **RSG rather than a RG** companion. But may be lower for sub-Chandra white dwarfs.
- If the scenario is correct, important **new constraints on both CE and WD explosion physics**.

Thank you!

Fe mass modelling



WD-RSG binaries



Population studies: $M^{max,final}_{companion} \sim 20\ M_\odot$ e.g. Willems & Kolb 2004

Plunge-in

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THE CRITICAL RADIUS AND THE EQUIVALENT RADIUS OF THE LAGRANGIAN LOBE FOR A BINARY SYSTEM

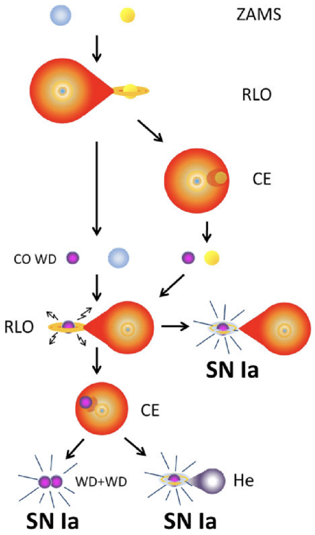
$q = M_W/M_R$ (Mass ratio WD to RG)	$R_R{}^*/R_{OR}$ (Largest allowed RG radius for stable orbit (units of WD orbital radius))	r_{eq}/R_{OR} (Roche lobe radius)
1	1.186	0.378
0.8	1.060	0.398
0.6	0.918	0.424
0.4	0.750	0.461
0.3	0.649	0.486
0.2	0.530	0.521
0.15	0.459	0.546
0.1	0.375	0.578
0.05	0.265	0.626

RG expands to Lagrangian lobe while orbit still stable (q = 1 to 0.2)

Orbit becomes unstable before RLOF (q = 0.15 to 0.05)

- If the companion is massive enough (>5 times the WD mass), the system will never settle into RLOF accretion but the WD will plunge into the companion.

Explosion



1. **Merger with a RG (AGB) star.** WD-RG CE merger likely channel to produce WD-WD close binaries (normal Ia progenitors). With an AGB star companion another WD ready (→ Super-Chandra merger explosion). Some tension with estimated CSM mass in SN 2006gy.
2. **Merger with a RSG.** Sub-Chandra double detonation explosion as WD merges with He core. No tension with estimated CSM mass.

Ivanova 2013.