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

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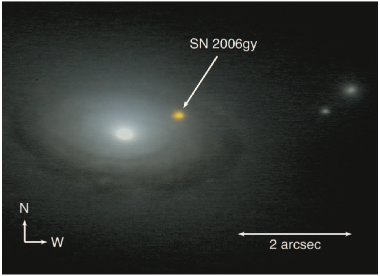

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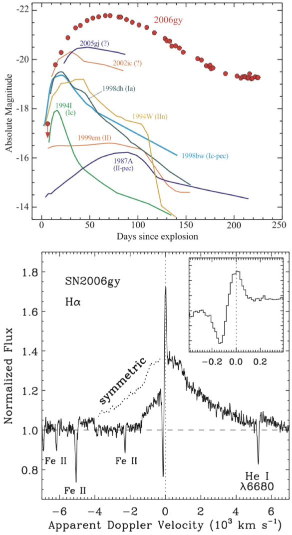
Superluminous supernova SN 2006gy - one of the brightest SNe ever seen

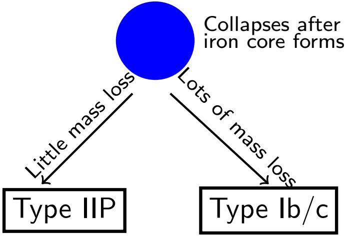
- Radiated energy $\sim \mathbf{10^{51}}$ erg (compare $\sim 10^{49}$ erg normal SNe).
- **Interaction with a massive ($\sim 10\ M_{\odot}$) slow-moving ($\sim$ 100 km/s) CSM indicated** from narrow H lines (Type IIn). This CSM ejected $\lesssim$ 100y before the SN.
- A vast and diverse set of models proposed: e.g. *pulsational pair instability SN, a LBV core-collapse soon after a Eta-Carina like eruption,...* All of them involve the explosion of a **massive star**.



Smith et al. 2007

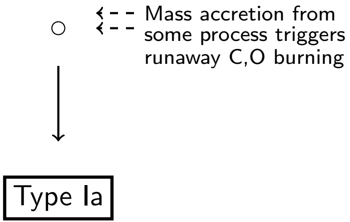
The supernova landscape

Massive star



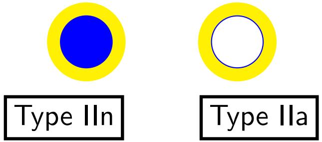
- $E \sim 10^{51}$ erg
- $M_{ej} \approx 10\ M_\odot$
- $M(^{56}\mathrm{Ni}) = M(\mathrm{Fe}) \approx 0.05\ M_\odot$

White dwarf



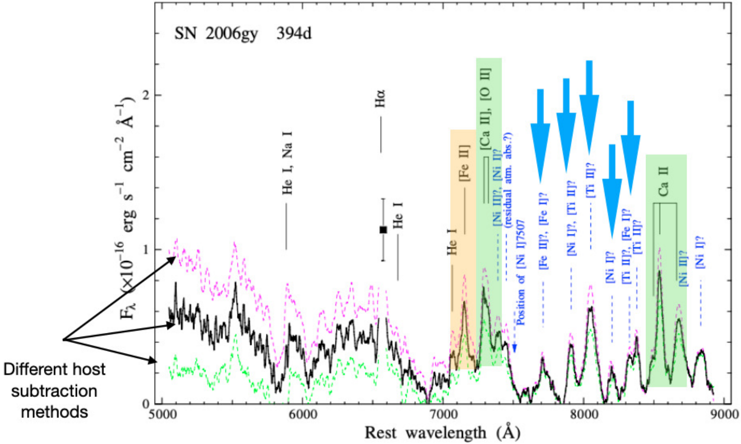
- $E \sim 10^{51}$ erg
- $M_{ej} \approx 1\ M_\odot$
- $M(^{56}\mathrm{Ni}) = M(\mathrm{Fe}) \approx 0.5\ M_\odot$

Sometimes : CSM interaction



Discovered 2003 (Hamuy et al.)

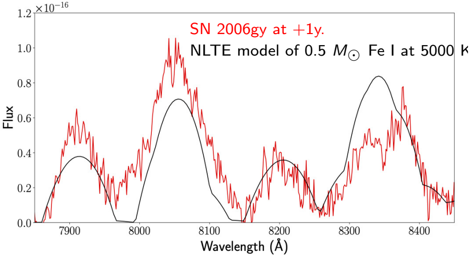
Strange, unknown emission lines seen at $+1y$ *Kawabata et al 2009*

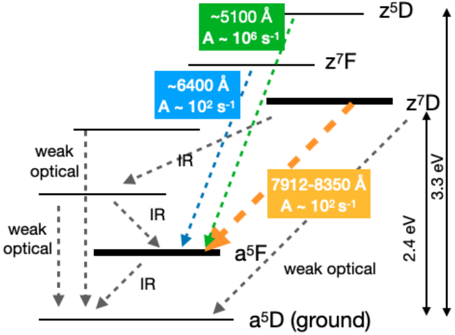


- Line widths $\rightarrow$ 1500 km s^{-1} expansion.

Identification : Fe I *Jerkstrand, Maeda & Kawabata 2020, Science*

These lines not seen before in any SN.





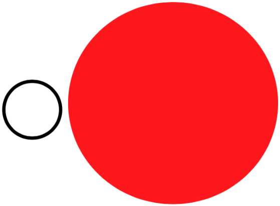
Modelling of the lines constrains the iron mass to $\boxed{0.3 < M_{Fe} < 2.1\ M_\odot}$

In addition, the brightness of the spectrum at +1y matches the decay of 0.5 $M_\odot$ ^{56}Ni.

- **Pulsational PISNe**: $M_{Fe} = 0$. Ruled out.
- **Core-collapse SNe** : $M_{Fe} \lesssim 0.2\ M_\odot$, too low. Also no O lines seen.

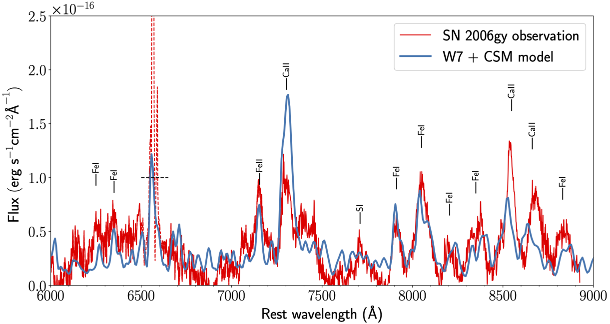
Is SN 2006gy the results of a white dwarf merging with a massive star, ejecting a CE, and then exploding as a Ia SN?

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



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

Spectral simulations with the SUMO NLTE code.

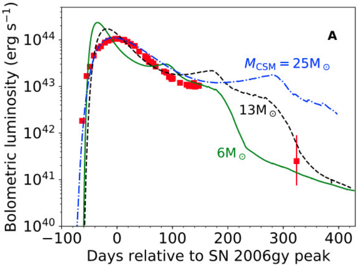


- Fe I lines emerge.
- No flux rescaling - a major strength of the model.
- Physical conditions (temperature, ionization) satisfactory.

Testing the idea: The light curve properties also work out

Here 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).

Summary

- **A large iron reservoir** ($\sim 0.5\ M_\odot$) identified in the superluminous Type IIn supernova SN 2006gy. This rules out several previous scenarios such as shell collisions (these are iron-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 to explain why a SN occurs soon after ($<$ 100y) CSM creation.
- Best-fitting CSM mass is 10-15 $M_\odot$ which would suggest a **RSG rather than a RG** companion.
- If the scenario is correct, important **new constraints on both CE and WD explosion physics**.

Thank you!

Terman+1994 : A WD spiralling into a 5 $M_\odot$ RG

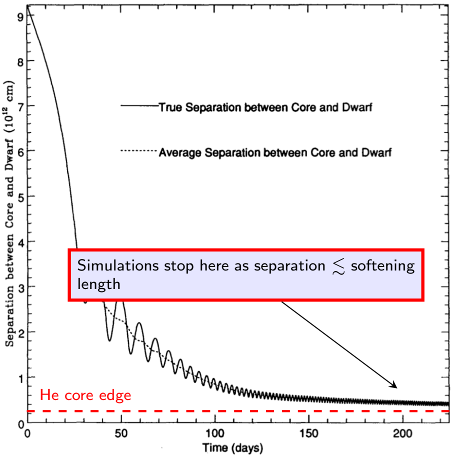
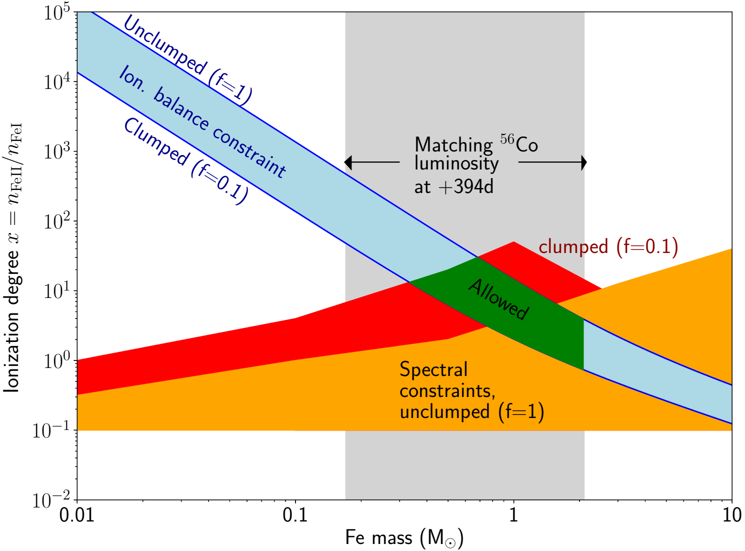


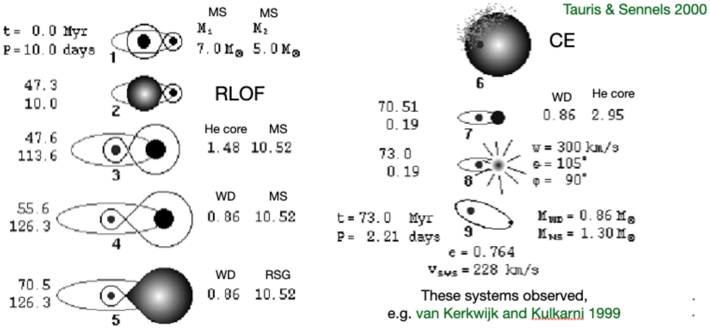
FIG. 1.—The variation of the orbital separation between the core of the red giant and the dwarf companion as a function of time. The solid curve corresponds to the actual separation between components, and the dashed line corresponds to the average separation. The separation is expressed in units of 10^{12} cm, and the evolution time is expressed in days.

- Ejection of whole envelope on time-scale few years.
- Similar simulations: Terman+1995 (NS into BSG, in-spiral time 5y), Yorke+1995, Sandquist 1998, Taam & Sandquist 2000.

Fe mass modelling



WD-RSG binaries



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

Plunge-in

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

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

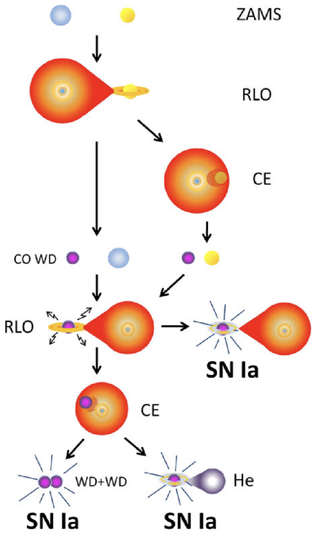
$q = M_W/M_R$ (Mass ratio WD to RG)	R_R^*/R_{OR} (Largest allowed RG radius for stable orbit (units of WD orbital radius))	r_{eq}/R_{OR} (Roche lobe radius)
1	1.186	0.378
0.8	1.060	0.398
0.6	0.918	0.424
0.4	0.750	0.461
0.3	0.649	0.486
0.2	0.530	0.521
0.15	0.459	0.546
0.1	0.375	0.578
0.05	0.265	0.626

RG expands to Lagrangian lobe while orbit still stable

Orbit becomes unstable before RLOF

- 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.

PISN light curves