Nebular spectra of superluminous supernovae

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MPA

Outline

1. Observational overview
2. Parameterized O-zone models
3. Pair-instability models

Papers :

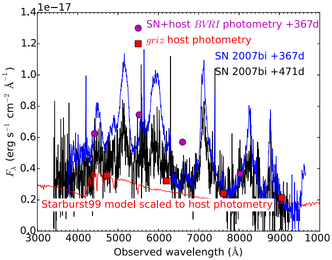
Jerkstrand, Smartt & Heger 2016 MNRAS
Jerkstrand, Smartt, Inserra, Nicholl, Chen, Kruhler, Sollerman, Taubenberger, Gal-Yam, Kankare, Maguire, Fraser, Valenti, Sullivan, Cartier, Young 2017 ApJ

Observational overview, spectra >200d post-peak

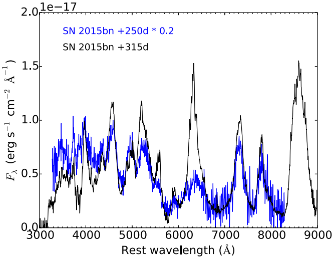
SN	z	Epochs	Telescopes	Coverage (Å)	Comment
SN 2007bi	0.13	+367, +471	VLT, Keck	3300-8500	
PTF12dam	0.11	+509	GTC	4000-8000	[O I]
iPTF13ehe	0.34	+251	Keck	3000-10000	Hα
PS1-14bj	0.52	+202	Magellan	6000-10000	O III
LSQ14an	0.16	+205, 414, 478	VLT	3000-20000	O III
SN 2015bn	0.11	+200-390	Mag., Gemini, VLT	3000-20000	07bi-clone
iPTF16bad	0.25	+242	Keck	4000-10000	Hα
Gaia16apd	0.10	+234, +399	GTC	6000-9000	[O I]
SN 2017egm	0.03	+126-353	MDM/MMT	3900-9200	weak [O I]
PTF09-12×5	~0.1	+241-527	Misc.	4000-10000	

Papers: Gal-Yam+2009, Chen+2015, Yan+2015,2017, Lunnan+2016, Nicholl+2016, Jerkstrand+2017, Inserra+2017, Kangas+2017, Quimby+2018, Nicholl+2019

- Quality varies a lot (redshift, decline rate, host brightness..)
- Typically severe host galaxy contamination at late times that needs removing

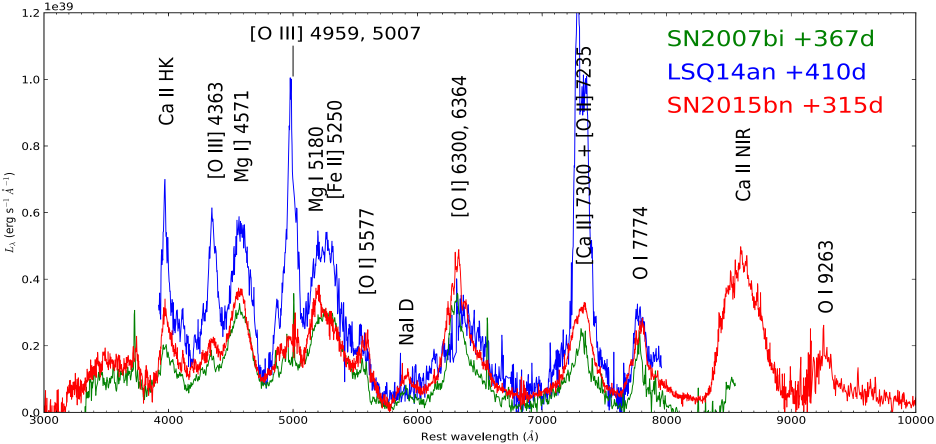


2007bi data: Gal-Yam+2009



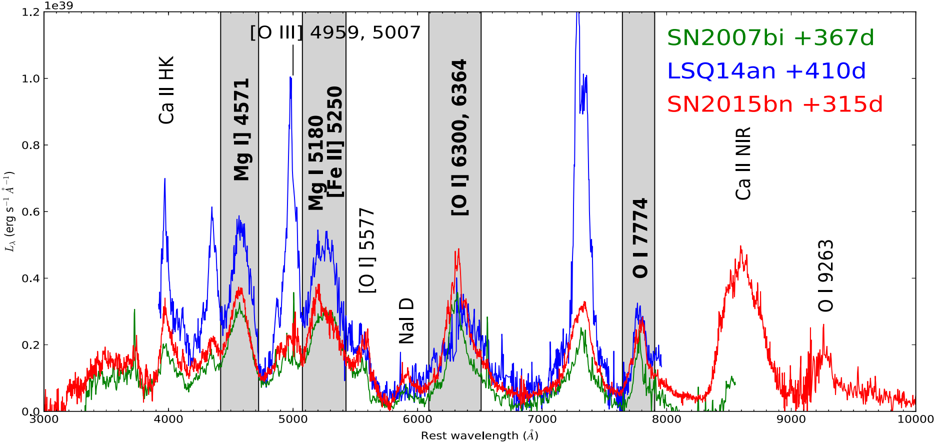
2015bn data: Jerkstrand+2017

Long-duration SLSNe at nebular times



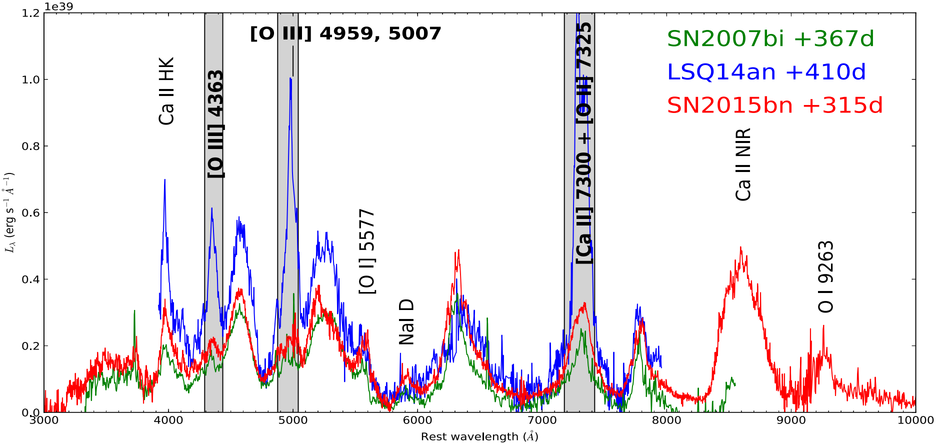
- O, Mg, Na, Ca clearly identified. Probably also Fe.
- Expansion velocities 3000-10000 km/s.

Long-duration SLSNe at nebular times



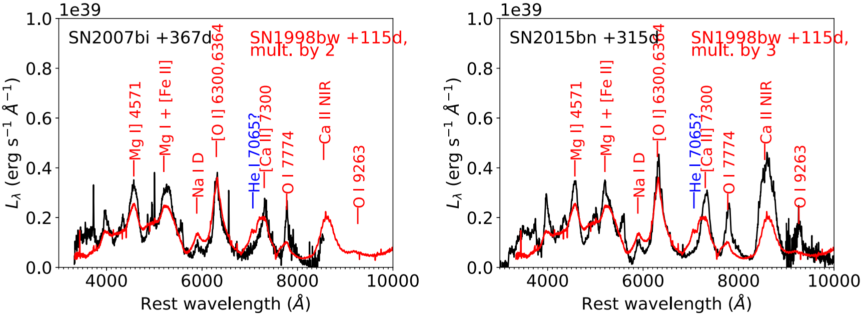
- Neutral lines: Similarity/homogeneity between the different SNe.
- O I 7774 narrower ($\sim$3000 km s^{-1}) than [O I] 6300, 6364, Mg I] 4571, Mg I/Fe II 5200 (5000-10000 km s^{-1}).

Long-duration SLSNe at nebular times



- Ionized lines (O II and O III): More diversity. As narrow as O I 7774.
- The 7300 Å line is strong when [O III] 4363 and [O III] 4959, 5007 are strong → probably dominated by [O II] 7325.

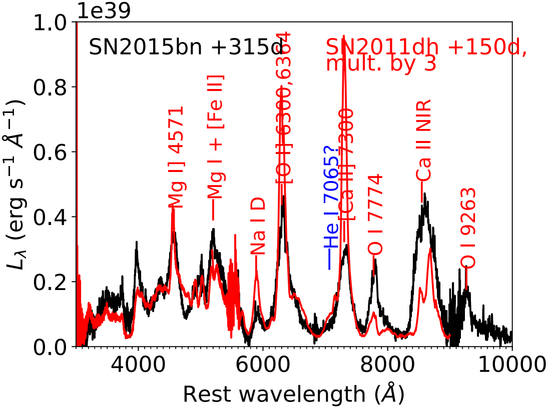
Strong similarity to GRB SNe such as SN 1998bw



1998bw data: Patat+2001

- Unlikely to involve fundamentally different scenarios.
- O I 7774 and O I 9263 stronger in the SLSNe. Can cool only at high density (Maurer & Mazzali 2010).
- Is 4000-5500 Å plateau due to large amounts of Fe and therefore evidence for ^{56}Ni?

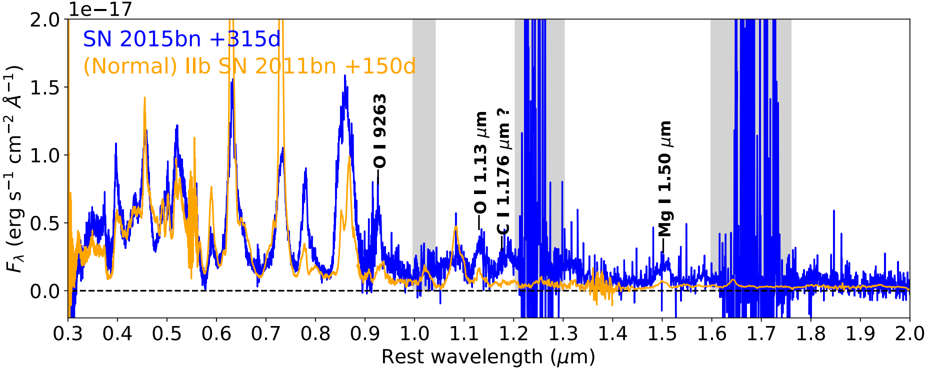
Also no major qualitative differences to normal Ib/Ic/IIb SNe (but the O II/O III lines are exceptions)



2011dh data: Ergon+2015

- The required time-shift is a first indication that SLSNe involve larger masses and/or are more clumped.

SLSNe in the near-infrared



- Not much flux in NIR compared to optical.
- Detections of O I 9263, O I 1.13 μm, Mg I 1.50 μm, maybe C I 1.18 μm. The IR O and Mg lines give important constraints on the ejecta (see later).
- No signs of He, Si, S.

Modelling the O-zone emission

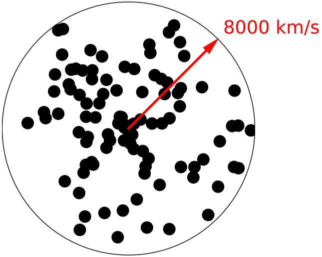
Approach : 1) Decouple ejecta properties from unknown power source (no strong E sensitivity for E$\gtrsim$ 1 keV)

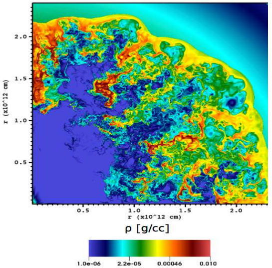
2) Investigate parameter space for M, f, e_{dep},..

Note: no attempt to model the whole spectrum, just O/Mg lines.

Fix $V = 8000$ km s^{-1}, $N = 100$ clumps, t=400d. Then vary:

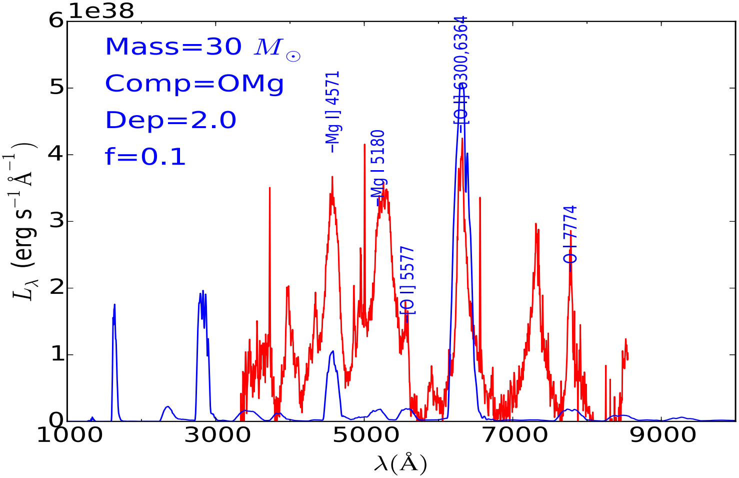
- Zone mass: $M = 3 - 30$ M$_\odot$
- Energy deposition: $d = 2 - 20 \times 10^{41}$ erg/s.
- Filling factor: $f = 0.001 - 0.1$
- Composition: Pure O, OMg, C-burn





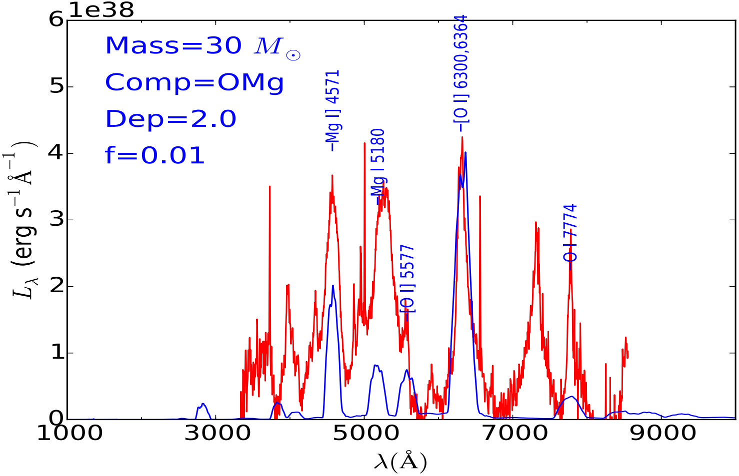
Chen+2016

Indications of clumping: 1. Mg I lines



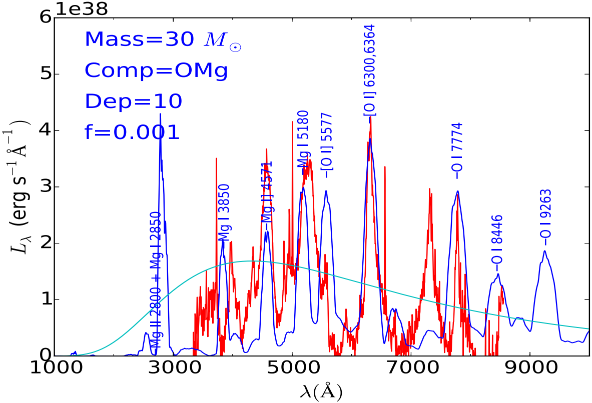
- High Mg I] 4571 luminosity requires cooling emission.
- Too large f : Mg fully ionized to Mg II → weak Mg I] 4571 cooling.

Indications of clumping: 1. Mg I lines



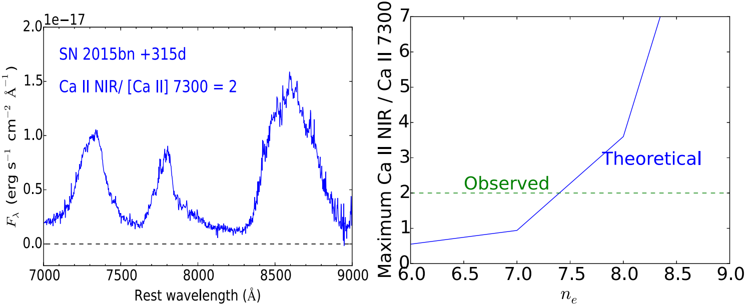
- Decrease f : Mg I fraction increases → Mg I] 4571 strengthens and Mg I 5180 emerges.
- O I recombination lines strengthen, and can get also cooling contribution.

Indication of clumping: 2. Blackbody limit for line strengths



- At very low f, spectrum formed under LTE optically thick conditions → line peaks follow blackbody.
- In models where Mg I] 4571 is reproduced, also Mg I 5180 tends to have similar strength → possibly important contributor to 5200 feature.

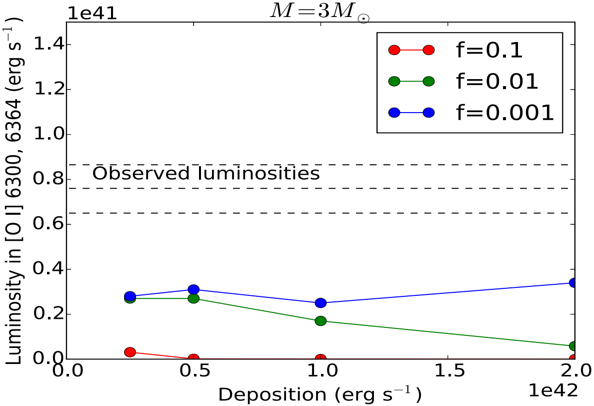
Indications of clumping. 3. The unusual Ca II line ratio, and O I recombination lines



- Observed ratio requires high electron density, $n_e \gtrsim 10^8$ cm^{-3}.
- Similar result from O I recombination lines ($n_e = 10^8 - 10^9$ cm^{-3})
- Need low filling factor to make reasonable ejecta masses from those n_e:

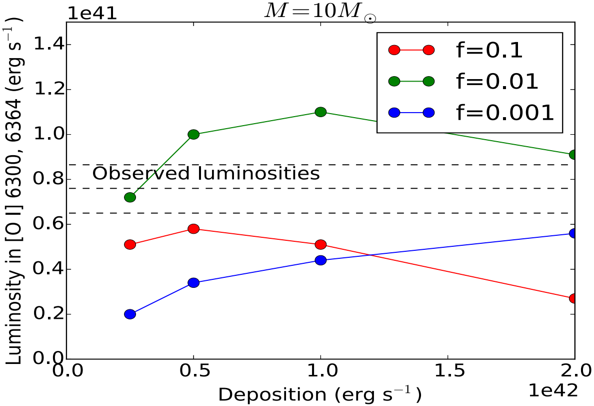
$$M = 3000\ M_\odot f \left(\frac{n_e}{10^8\ \mathrm{cm}^{-3}}\right)\left(\frac{\bar{A}}{40}\right)\left(\frac{x_e}{0.1}\right)^{-1}$$

Constraints on the O mass



- Models with 3 $M_\odot$ are over 3 times too dim for *any* deposition and density: oxygen ionizes to O II before temperature gets high enough for enough [O I] emission.
- Also Mg lines much too weak at zone masses ∼3 $M_\odot$.

Constraints on the O mass



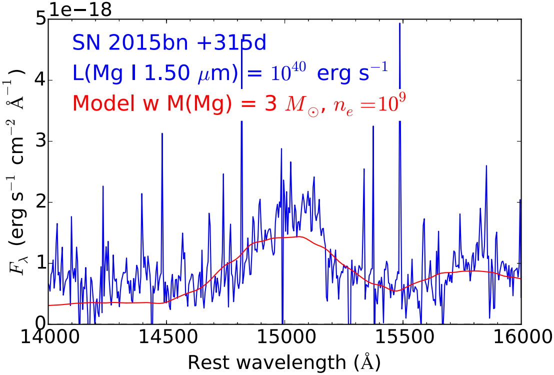
- Models with $\gtrsim$10 $M_\odot$ fare better.
- Complex curves due to competing effects of ionization, optical depth, not only for O but for other cooling lines.

Constraints on the Mg mass

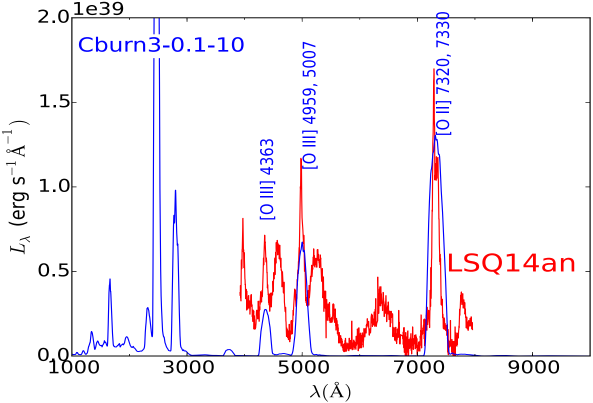
Mg I 1.50 μm expected to roughly follow recombination luminosity:

$$L = 1 \times 10^{40} \text{ erg s}^{-1} \times \left(\frac{M_{\rm Mg}}{15\ M_\odot}\right)\left(\frac{n_e}{10^8\ \text{cm}^{-3}}\right)\left(\frac{\alpha^{eff}(T)}{10^{-13}\ \text{cm}^3\text{s}^{-1}}\right) \qquad (1)$$

→ Mg masses of order 1-10 $M_\odot$.

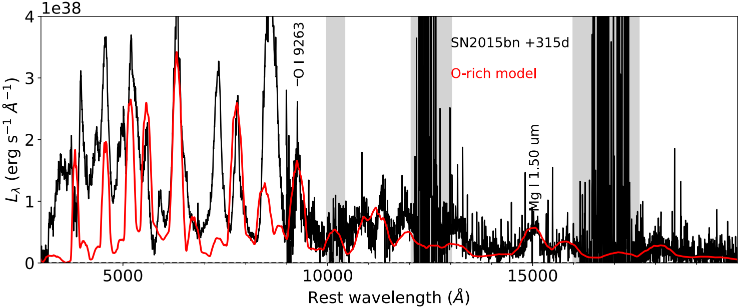


The O II and O III lines: evidence for a second ejecta component?



- Seen in PS1-14bj and LSQ14an. Velocities lower than neutral lines.
- Need large energy deposition into a low mass/low density region (here 3 $M_\odot$ at f=0.1)
- Inner pulsar wind nebula? Circumstellar interaction component?

A summary and overview; single OMg zone compared to SN 2015bn

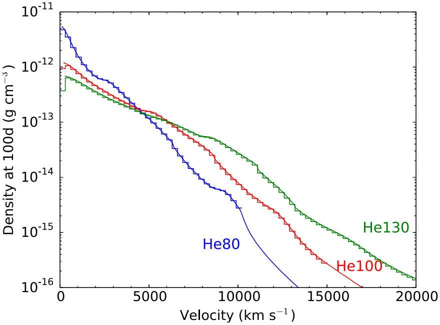


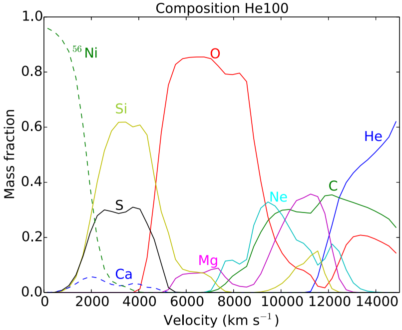
- The parameterized modelling points to needing ~ 10 $M_\odot$ OMg-rich composition, at significant compression. Plus a Ca-emitting zone.
- SNe with O II/O III lines may need a second lower-density component.

Pair-instability supernovae *Jerkstrand, Smartt & Heger 2016*

Compute spectra of 3 explosion models from Heger & Woosley 2002:

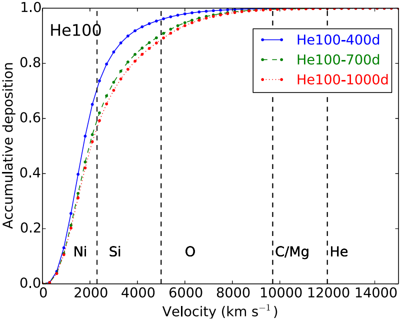
Model	V_{char} (km s^{-1})	O ($M_\odot$)	Si+S ($M_\odot$)	^{56}Ni ($M_\odot$)	Brightness
He80	5500	47	19	0.1	dim/normal
He100	7600	44	33	6	SLSN
He130	9700	33	35	40	SLSN

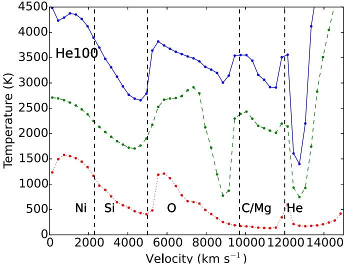


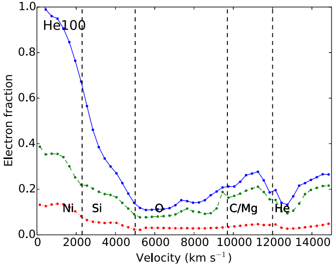


- 1D models expected to be accurate as mixing demonstrated to be weak (Joggerst & Whalen 2011, Chatzopoulos+2013, Chen+2014, Whalen+2015)

Physical conditions

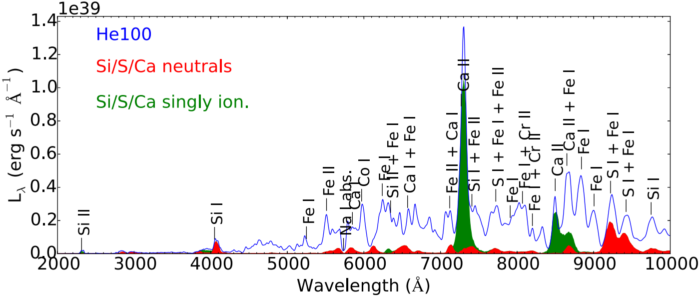


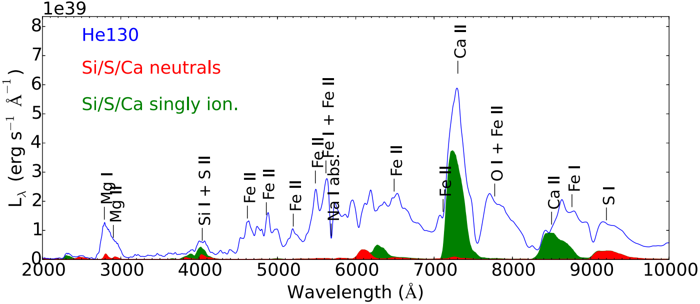




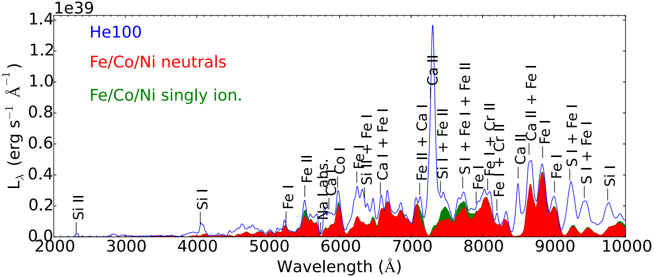
- Gamma rays fully trapped in ^{56}Ni and Si/S layers.
- Ejecta are cold and neutral.
- Expect lines of Fe I, Si I, S I, ...

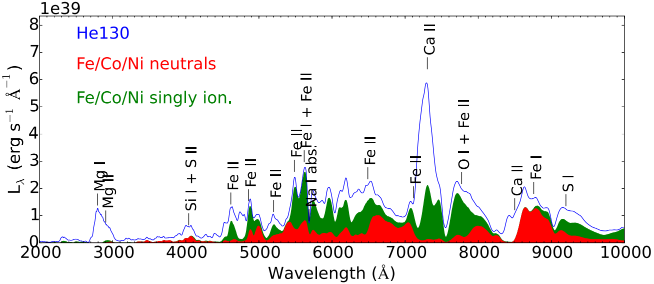
Intermediate contribution by Si/S/Ca



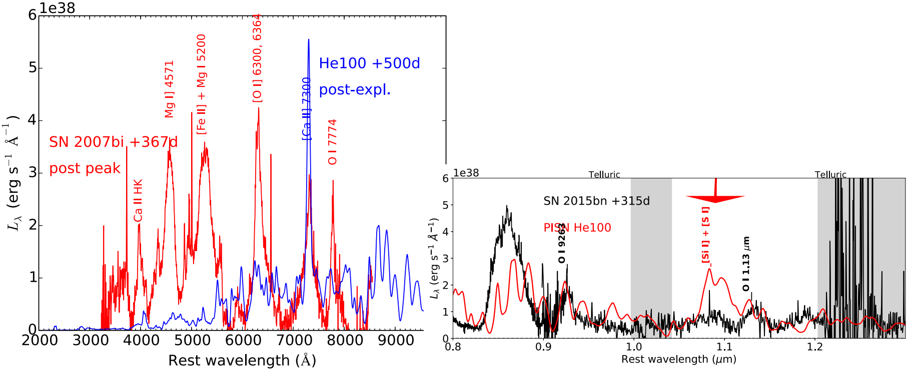


Strong contribution by Fe/Co/Ni





Pair-instability SNe: fit to broad-lined SLSNe is unsatisfactory



Jerkstrand, Smartt, & Heger+2016 (MNRAS), see also Dessart+2013

- No good fit to any SLSN Ic (SN2007bi, PTF12dam, LSQ14an, SN2015bn).
- *Qualitative* problems: No sign of massive (30 $M_\odot$) Si/S reservoirs either by emission or blocking of O-zone.
- Apart from spectral discrepancies, the SNe decline faster than ^{56}Co decay by factor 1.2-2.2.

SLSNe : overview of model classes and links to nebular spectra

Radioactivity

$E \approx 10^{51} \left(\frac{M(^{56}\mathrm{Ni})}{5\ M_\odot}\right)$

* Similarity to SN 1998bw and other broad-lined Ic.
* Blue plateau and 5200 line by Fe?
* PISNe too red. Massive CCSNe?
* Gamma-ray deposition at small f? Especially O II/OIII hard.

Neutron star rotation energy
$E \approx 10^{51} \left(\frac{P}{5\ \mathrm{ms}}\right)^{-2}$

* Pulsar wind could explain inferred compression.
* O II and O III lines may be from inner pulsar wind.
* Predictive test failed for PTF12dam : ad-hoc escape of magnetar radiation needed.
* Line profiles?

Ejecta kinetic energy
$E \approx 10^{51}$

* Shock region could explain small f and O II/O III.
* Why no narrow He,C,O lines from unshocked CSM? (compare IIn SNe)
* Large inferred O masses problematic, at least for PPISNe.

Summary

- There are now nebular-phase ($t > 200d$) observations of $>$10 SLSNe, z$\sim$0.1.
- Type Ic SLSNe show a significant degree of homogeneity, and strong similarity with GRB-powered SNe such as SN 1998bw.
- However, a few unique properties include O II and O III lines, sometimes broad Hα, and strong O I 7774.
- Parameterized single-zone models show that the [O I] 6300, 6364 luminosity can only be reproduced in models with M(O-zone) $\gtrsim$ 10 M$_\odot$. Mg I] 1.50 μm constrains the Mg mass to several M$_\odot$, supporting the picture of quite massive ejecta.
- A high degree of clumping is indicated, filling factor $f_O \lesssim 0.01$. Calcium lines indicate high electron densities $n_e \gtrsim 10^8$ cm^{-3}.
- Nebular models of PISNe show cold and neutral ejecta, with iron/silicon/sulphur dominating the spectrum. Agreement with observed spectra of long-duration SLSNe is unsatisfactory.