Modelling and interpretation of spectra of superluminous supernovae

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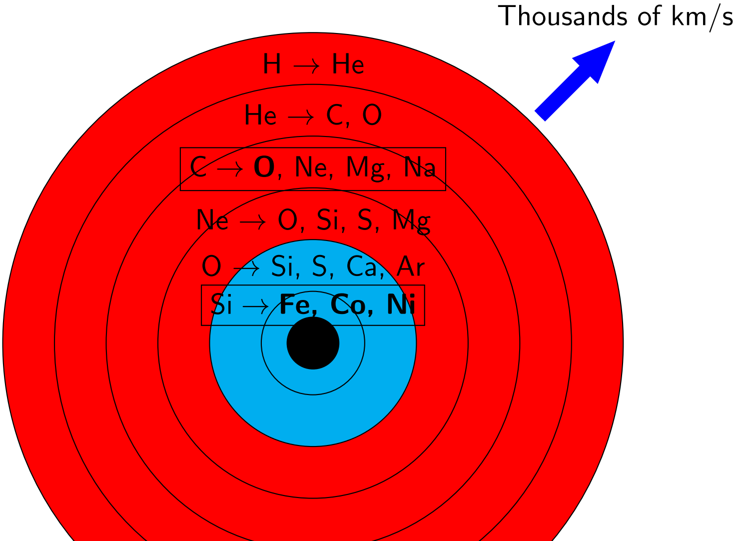
The need for spectral modelling of SLSNe

- Since about 10y ago, clear that several scenarios and mechanisms exist that can explain SLSN light curves. However, these have enough physical freedom in them that from light curves alone the solutions are typically degenerate.
- Spectral formation is, on the other hand, governed my microphysics which is well understood and sophisticted synthesis codes exist. In addition to this, with spectra we go from basically 2-3 observables (light curve duration, brightness level, tail decline) to dozens. We need this information to get further.

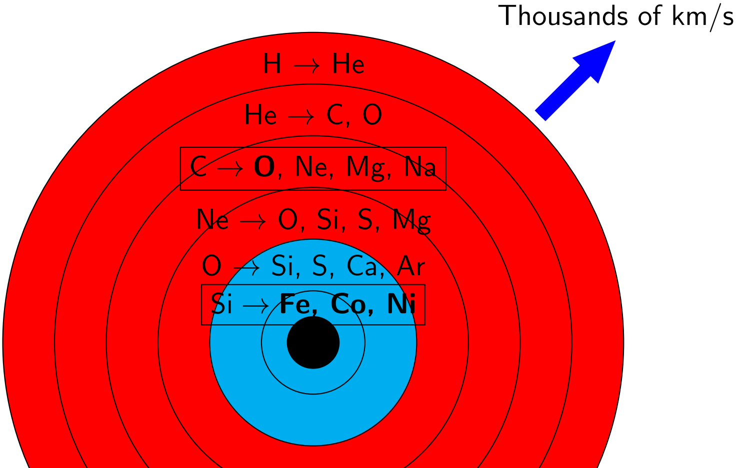
Nucleosynthesis in supernovae

- Hydrostatic (pre-SN) burning: main tracer is **oxygen**.
- Explosive SN burning: main tracers are **iron, cobalt, nickel**.

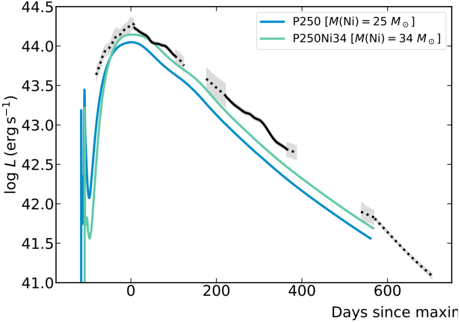


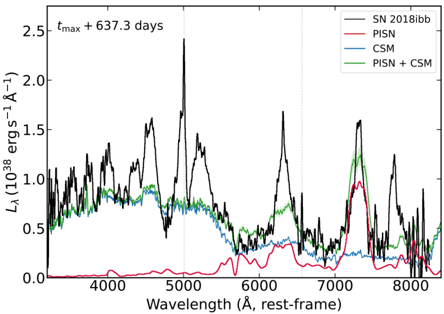
Nucleosynthesis in supernovae

- **Element masses**? Constrains progenitor.
- **Distribution and physical conditions**? Constrains explosion and powering mechanism.
- Determination of these properties best done in the **nebular phase**.



[Co II] lines in SN 2018ibb Schulze+, submitted

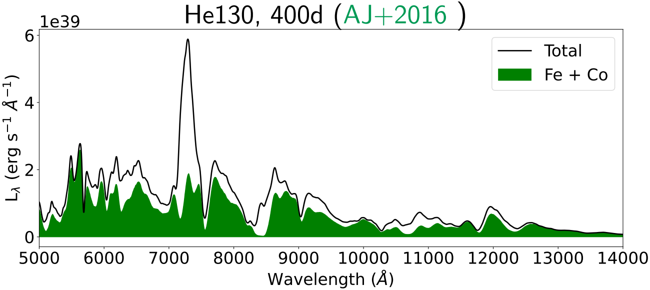




- The SN shows good agreement with PISN light curve models.
- Straight comparison with PISN models shows the usual discrepancy of blue excess (Dessart+2013, AJ+2016); however a possible solution is here proposed that PISNe unavoidably come with a CSI emission component.

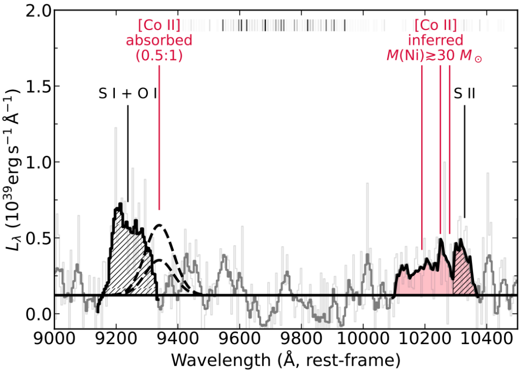
[Co II] lines in SN 2018ibb Schulze+, submitted

- One unique property of (superluminous) PISN models is the huge ^{56}Ni mass. *Can we see direct emission lines from the associated Co and Fe?*
- Models give almost a quasi-continuum of many blending lines of similar strength → not many clear "smoking-gun" lines. Overall pattern not matching any observed candidates.



- There is also a lot of opacity still at 400d → significant scattering/fluorescence effects.

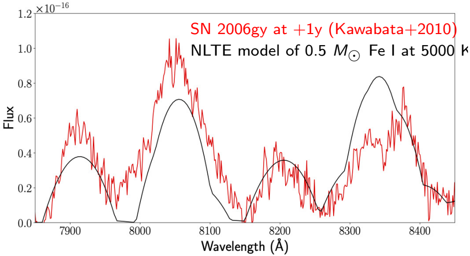
[Co II] lines in SN 2018ibb Schulze+, submitted

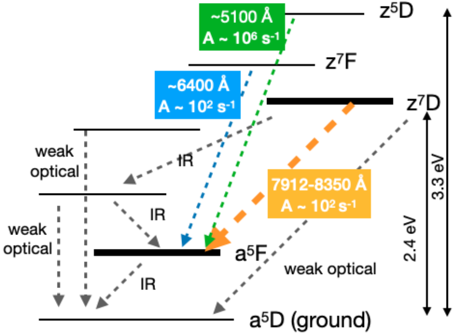


- **[Co II] 1.025 μm** is the strongest predicted Co line in SNe at nebular times (e.g. AJ+2015), closely followed by **[Co II] 9340**.
- If the emission at 1.02 μm in 2018ibb is interpreted as Co II, the initial ^{56}Ni mass is $\gtrsim$ 30 $M_\odot$.
- However, [Co II] 9340 is not seen, which requires postulation of absorption of this line.

Identification of a large iron reservoir in SN 2006gy

Jerkstrand, Maeda & Kawabata 2020, Science

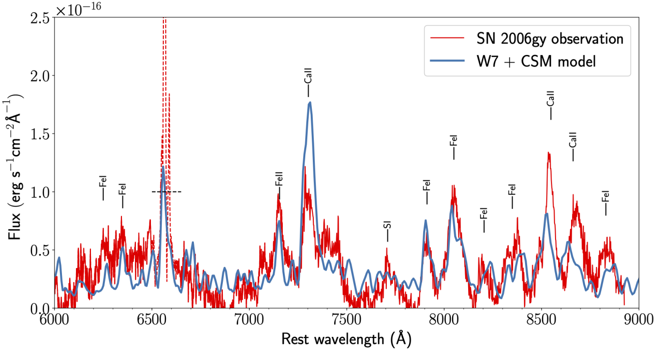




- Modelling of the lines constrains the iron mass to $\boxed{0.3 < M_{Fe} < 2\ M_\odot}$.
- Also, the brightness of the spectrum at +1y matches the decay of an initial 0.5 $M_\odot$ of ^{56}Ni.
- The iron mass is too low for a PISN; we instead favor an interpretation of 2006gy as a **Ia-CSM supernova**.

Testing the Ia-CSM scenario: Spectrum of a decelerated Ia SN at +1y fits quite well.

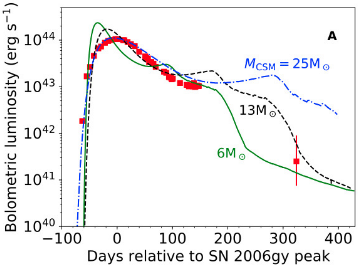
Spectral simulations with the SUMO NLTE code. W7 ejecta model with scaled down velocities (factor 7), with a few solar masses CSM mixed in.



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

Testing the Ia-CSM scenario: Spectrum of a decelerated Ia SN at +1y fits quite well.

Light curves: 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.

White dwarfs merging with red (super)-giants? An early idea for SNe that was then forgotten

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

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Received 1973 June 18; revised 1973 September 13

ABSTRACT

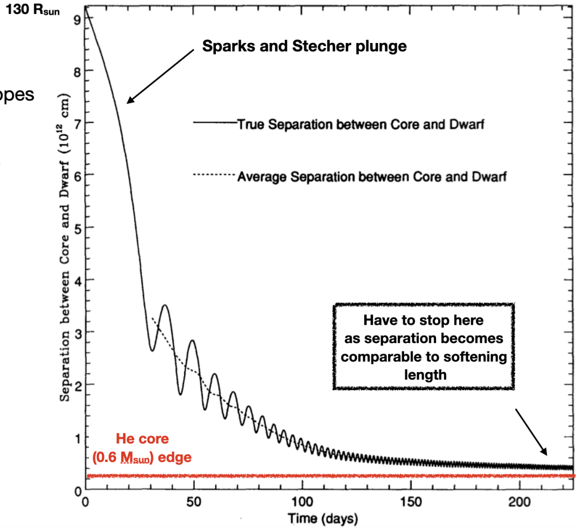
The proposed model is a binary consisting of a white dwarf and a star evolving toward the red-giant branch. Conditions are given under which the revolution period of the binary and the rotation period of the red giant will reach a synchronous state and under which no stable synchronous orbit is possible. 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.

White dwarfs merging with red (super)-giants? An early idea for SNe that was then forgotten

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

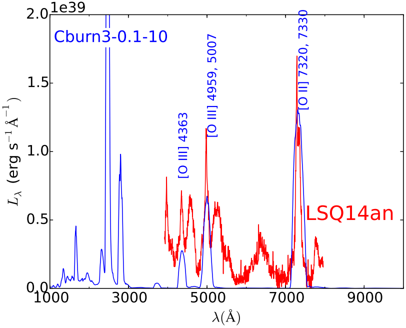
e.g. Terman+1995, Yorke+1995, Sandquist 1998, Taam and Sandquist 2000

Terman+1994 : 1 M_{sun} WD into a 5 M_{sun} RG



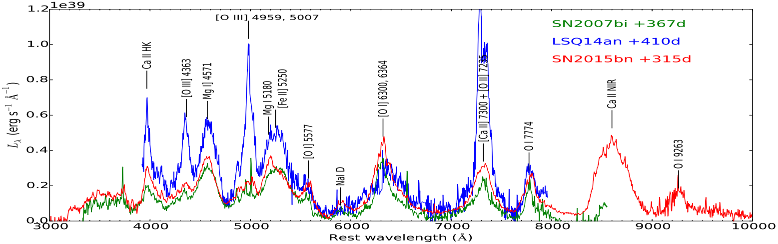
Oxygen lines in SLSNe

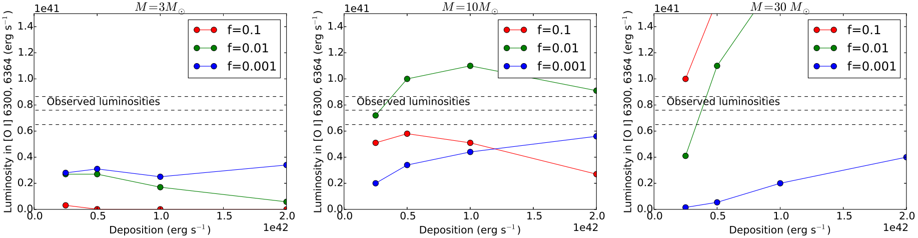
- **Neutral oxygen**: [O I] 6300, 6364 a workhorse diagnostic line in CCSNe and SLSNe. Also recombination lines (O I 7774, 9263, 1.13 μm) can be sometimes be used.
- **Singly ionized oxygen**: [O II] 7325 (four lines between 7320-7330 Å). Coincides ($\Delta\lambda_0/\Delta\lambda_{Doppler} \ll 1$) with [Ca II] 7291, 7323 and often hard to know which is the dominant one.
- **Doubly ionized oxygen**: [O III] 4959,5007 and [O III] 4363. First identified in PS1-14bj and LSQ14an (Lunnan+2016).



AJ+2017

Slow-evolving Type I SLSNe : Highest O masses inferred from [O I] 6300, 6364 so far in any SNe ($\gtrsim 5\ M_{\odot}$) AJ+2017





Oxygen line formation

Optically thin line formation (taking $Z(T) \approx n_g$): Omand & Jerkstrand 2023

$$n_e > n_{e,crit} : L_{LTE} = \mathrm{const}_1 \times M_{\mathrm{ion}} h\nu e^{-T_{\mathrm{exc}}/T} \times A \quad (1)$$

$$n_e < n_{e,crit} : L_{NLTE} = \mathrm{const}_2 \times M_{\mathrm{ion}} h\nu e^{-T_{\mathrm{exc}}/T} \times \Upsilon n_e \quad (2)$$

Line	T_{exc} (K)	A (s^{-1})	Υ	$n_{e,crit}$ (cm^{-3})
[O I] 6300, 6364	22,800	7.5×10^{-3}	0.10	3×10^6
[O II] 7325	58,200	0.13	1.7	4×10^6
[O III] 4959,5007	29,200	0.025	1.9	5×10^5

- For slow-evolving Type I SLSNe electron densities well above these $n_{e,crit}$ values have been inferred. Then three equations (Eq. 1) for four unknowns (M_{OI}, M_{OII}, M_{OIII}, T).
- However, analytic O mass determination in SNe suffers from the fact that $T \ll T_{exc}$, which gives a very large error from T uncertainty. For this reason we mainly use **forward models** that self-consistently link mass, ionization, and temperature.

Oxygen line formation

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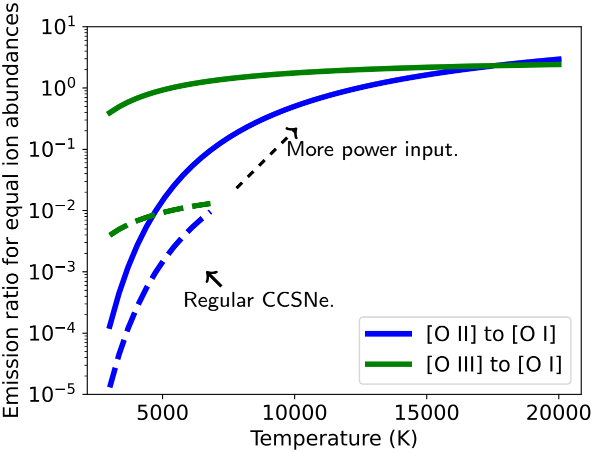
- For analytic treatment, also need to consider whether lines are actually optically thin.

$$\tau \approx 0.1 \left(\frac{A}{7.5 \times 10^{-3}}\right) \left(\frac{\lambda}{6300}\right)^3 \left(\frac{M}{1\ M_\odot}\right) \left(\frac{V}{5000\ kms^{-1}}\right)^{-3} \left(\frac{f}{0.1}\right)^{-1} \left(\frac{t}{1\ y}\right)^{-2} \quad (3)$$

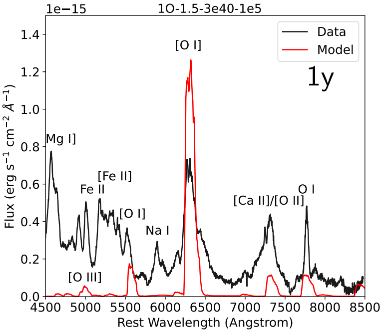
Oxygen line ratios in optically thin LTE limit

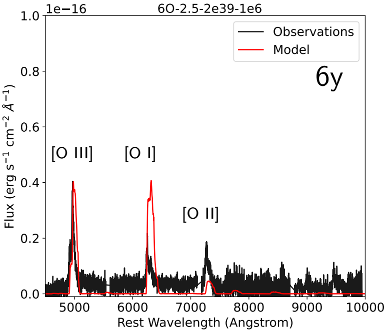


- To make [O II] noticable, need $T \gtrsim 8000$ K and/or $x(\mathrm{O\ II})/\mathrm{x}(\mathrm{O\ I}) \gg 1$.
- To make [O III] noticable, need $x(\mathrm{O\ III})/\mathrm{x}(\mathrm{O\ I}) \gtrsim 0.1$.

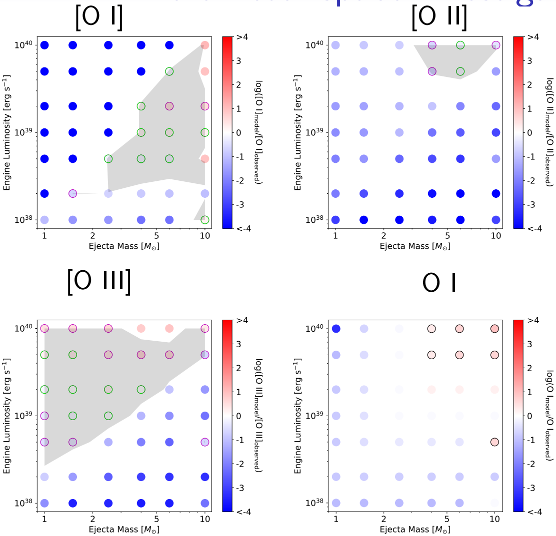
Modelling of pulsar wind powered SNe

- Progress with the magnetar model for SLSNe requires realistic spectral models to be developed.
- First steps laid down in SUMO (Omand & Jerkstrand 2023).
  - Injection of high-energy photons at inner boundary.
  - Self-consistent computation of ionization state and temperature in 1-zone model over parameter space of (L_{pwn}, T_{pwn}, M_{ejecta}).
  - Specific comparisons to SN 2012au which has [O I], [O II], [O III] lines.





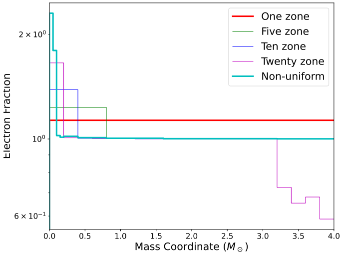
Parameter space investigations

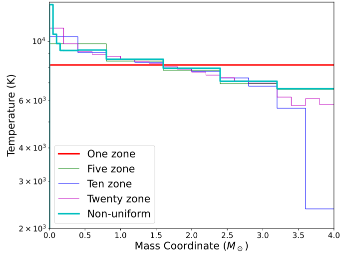


6y, $T_{pwn} = 10^5$ K

- Model temperatures are $\lesssim$ 6000 K, so high ionization drives emergence of [O II] and [O III] lines rather than temperature.

Need for multi-zone modelling





- X-rays have a much shorter mean-free-path than gamma-rays. This causes a **qualitative difference to radioactivity-powered SNe where physical condition gradients are stronger**.
- Thus, multi-zone modelling is more important (also for a uniform composition ejecta), and we are **more sensitive to the specific morphology**. This is basically SNR modelling, but as higher densities than normal.

Summary

- Nebular lines of **cobalt and iron** has recently led to progress in understanding SLSNe (e.g. SN 2006gy, SN 2018ibb). Both SNe are interpreted as thermonuclear explosions (Ia-CSM SN in one case, PISN-CSM in other).
- Nebular lines of **neutral oxygen** indicate large O masses in slow-evolving SLSNe, certainly larger than in regular Ibc SNe.
- Nebular lines of **ionized oxygen (O II and O III)** are seen in some SLSNe, and will almost certainly give us important constraints.
- Work is underway to **test the magnetar scenario** with realistic spectral synthesis modelling : sensitivity to specific morphology is here the main challenge.