Supernova abundance analysis with NLTE spectral models

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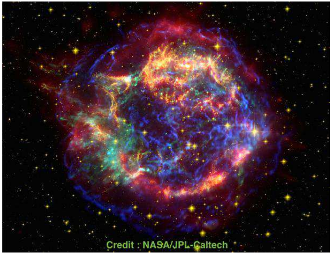
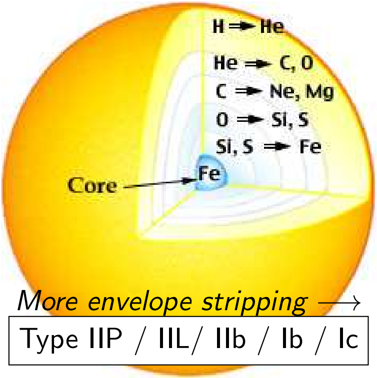


MARIE CURIE ACTIONS

Supernovae - the death of stars

1 Core-collapse of a **massive star** ($M \gtrsim 8\ M_\odot$) as it runs out of fuel at the end of its life (80%)

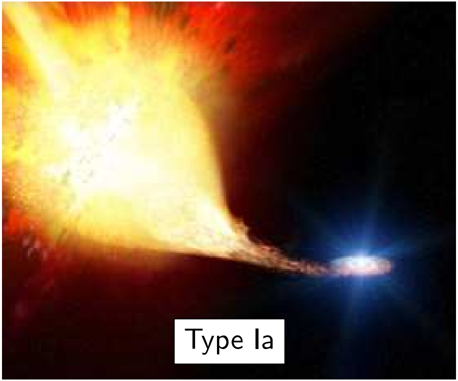


More envelope stripping →

Type IIP / IIL/ IIb / Ib / Ic

Credit: www.phys.olemiss.edu

2 Thermonuclear explosion of a **white dwarf** exceeding the Chandrasekhar limit (1.4 $M_\odot$) (20%)



Type Ia

Credit: hetdex.org

The origin of the elements

CCSN : Core-collapse supernova. TNSN: Thermonuclear supernova

Ab.	El.	Main source	Nebular lines seen in SNe
1	H	Big Bang	Many
2	He	Big Bang	He I 5016, 7065, 1.08 μm, 2.06 μm
3	O	CCSN	[O I] 5577, **[O I] 6300, 6364**, O I 7774, O I 9263 + ..
4	C	AGB stars+CCSN	[C I] 8727, 9824/9850, 1.44 μm, CO lines
5	Fe	CCSN+TNSN	[Fe II] 7155, 1.26 μm, 1.64 μm, 18 μm, 26 μm
6	Ne	CCSN	[Ne II] 12.8 μm
7	Si	CCSN+TNSN	[Si I] 1.10 μm, 1.20 μm, 1.60/1.64 μm, SiO lines
8	N	AGB stars	[N II] 6548, 6583
9	Mg	CCSN	Mg I] 4571, 1.50 μm
10	S	CCSN	[S I] 1.082 μm, 1.13 μm
11	Ar	CCSN	[Ar II] 6.99 μm
12	Ni	CCSN+TNSN	**[Ni II] 7378**, 1.93 μm, 6.6 μm, 10.7 μm, [Ni I] 3.1 μm
13	Ca	CCSN	[Ca II] 7300, NIR triplet, Ca I 4200
14	Al	CCSN	-
15	Na	CCSN	Na I 5890, 5896, 1.14 μm

Still few quantitative direct source results

Spectral synthesis modelling: the SUMO code *Jerkstrand 2011, PhD thesis, Jerkstrand, Fransson & Kozma 2011, Jerkstrand+2012, later updates..*

Radioactive decay and γ-ray transport

NLTE statistical equilibrium

- 22 of 28 elements from H to Ni, 3 ionization stages, ~100 excitation states each

Distribution of Compton electrons

- Spencer-Fano equation

Temperature

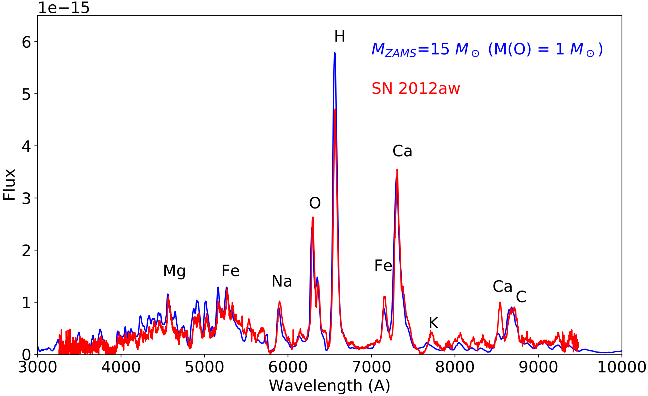
- Heating = cooling

Radiative transfer

- Monte Carlo method
- Sobolev approximation
- 300,000 atomic lines, 3,000 bound-free continua, free-free, electron scattering

- Code is 1D but allows for mixing by 'virtual grid' option

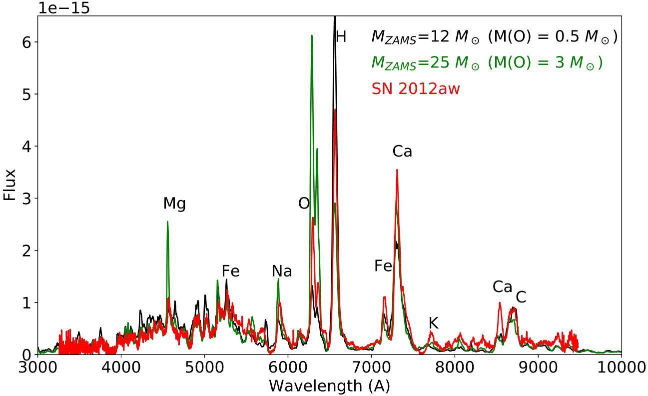
Diagnosing hydrostatic element production: example of oxygen



Jerkstrand+2014

- Only last 5-10 years have self-consistent spectral models in reasonable agreement with observed spectra emerged.
- Can now test stellar evolution and explosion models in detail, and determine nucleosynthesis yields to within factor $\sim$2.

Diagnosing hydrostatic element production: example of oxygen



Jerkstrand+2014

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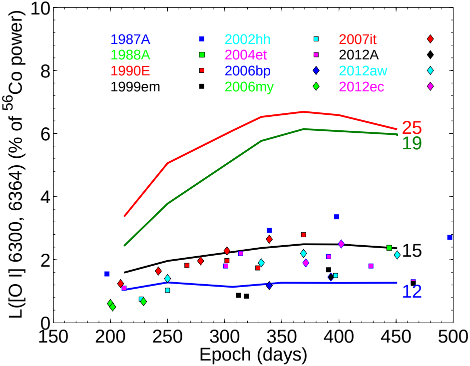
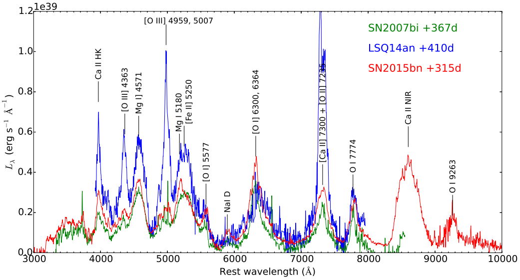
Oxygen yields in RSG explosions *Jerkstrand+2015 ,MNRAS*

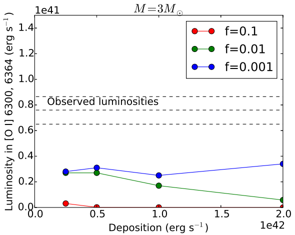
- 18-30 $M_{\odot}$ RSGs do not seem to explode. Are they collapsing directly to black holes? *See also Smartt 2009 for progenitor detection perspective.*

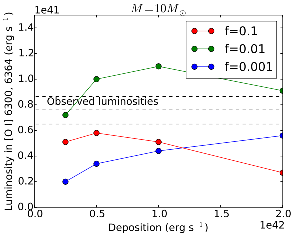


- Same picture for H-stripped SNe (Jerkstrand,Ergon,Smartt+2015, A&A).
- Problem for standard GCE models where these stars make most O.

The brightest Ic SNe : Highest O masses inferred so far ($\gtrsim$ 5 $M_\odot$). This means *some* massive stars do explode AJ+2017





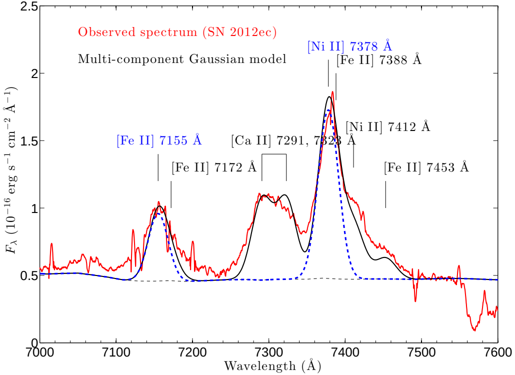


f=volume filling factor

- High ionization lines (O II, O III) hold clue to still unknown powering mechanism.
- Ejecta are significantly clumped.

Diagnosing iron-group production: example of nickel

- Main diagnostic line: **[Ni II] 7378**



Jerkstrand+2015,MNRAS

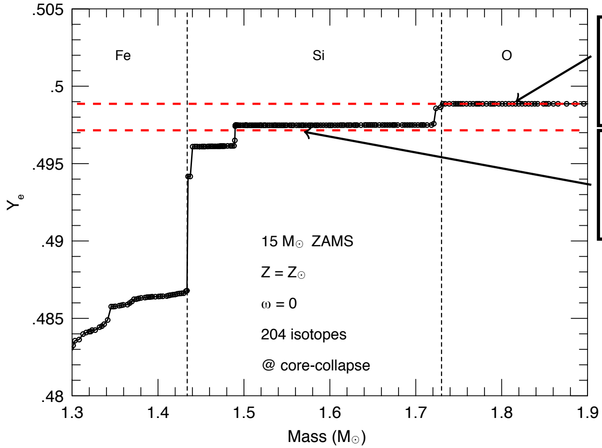
- Use forward model to identify which lines present in spectral region (result: 7) and in which regime they form
- Make 4-component fit (atomic data constraints remove 4 DOF) for $L_{\mathrm{Ni\ II}\ 7378}$, $L_{\mathrm{Fe\ II}\ 7155}$, $L_{\mathrm{Ca\ II}\ 7300}$, ΔV
- Obtain Ni/Fe ratio analytically

Ni/Fe ratios in 7 CCSNe *Jerkstrand+2015, MNRAS*

SN	Ni/Fe (times solar)	Reference
SN 1987A	$0.5 - 1.5$	Rank+1988, Wooden+1993, Jerkstrand+2015
SN 2004et	~ 1	Jerkstrand+2012
SN 2012A	~ 0.5	Jerkstrand+2015
SN 2012aw	~ 1.5	Jerkstrand+2015
SN 2006aj	$2 - 5$	Maeda+2007, Mazzali+2007
SN 2012ec	$2.2 - 4.6$	Jerkstrand+2015
Crab	$60 - 75$	Macalpine+1989, Macalpine+2007

- Average ratio $\geq$ solar.
- If true in larger sample, Type Ia must make Ni/Fe $\leq$ solar $\rightarrow$ constraints on both CCSN and TNSN explosions models.

Ne/Fe ratio is a diagnostic of which progenitor layer was explosively burnt *Jerkstrand, Timmes, Magkotsios+2015, ApJ*



Oxygen layer: Ye $\sim$ 0.499. Gives Ni/Fe $\sim$ solar

Silicon layer: Ye $\sim$ 0.497. Gives Ni/Fe $\sim$3 times solar

Important constraints on explosion mechanism and "mass cut"

NLTE solutions and current atomic data situation

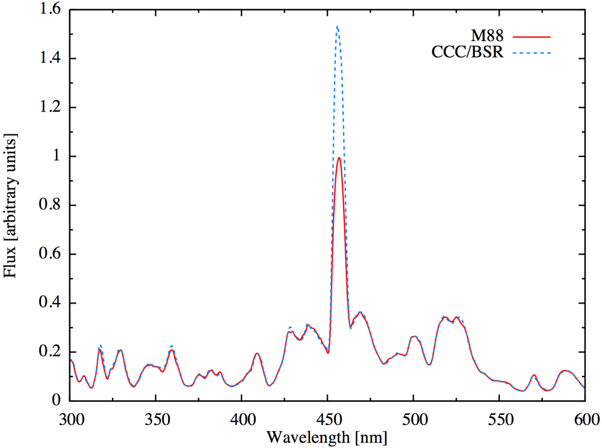
SUMO treats 60 atoms/ions in NLTE, ∼ 150 levels each → ∼10,000 level solutions in each zone and ∼300,000 transitions with specific atomic data.

- **Energy levels** : Good
- **A-values** : Good
- **Thermal collision strengths** : Medium, probably cover most important (low-lying) transitions
- **Non-thermal collision cross sections** : Poor, mostly Bethe approximation
- **Photoionization cross sections** : Medium. GS ok, meta-stable some
- **Recombination rates** : Medium
- **Charge transfer rates** : Poor. 150 rates, lack for many important metal-metal reactions

Current reference library maintained at
https://star.pst.qub.ac.uk/wiki/doku.php/users/ajerkstrand/start

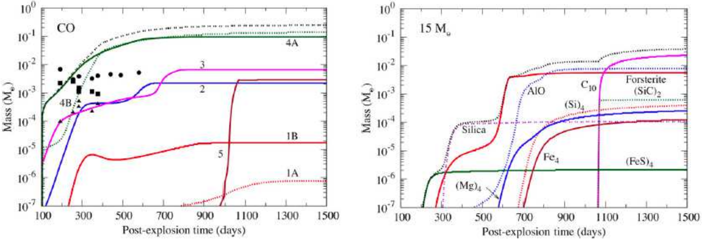
NLTE solutions and current atomic data set

Example how models still change with new atomic data for common atoms: New thermal collision strengths from Barklem+2017 (- - -)in Type Ib SN model:



Outlook and ongoing work

- **Chemistry**: Molecule and dust formation known to be important in SNe.



Sarangi & Cherchneff 2013

- **r-process elements**: For kilonova modelling and advanced supernova modelling. See talk by Jon Grumer later today for first GRASP2K + SUMO results.
- **Full 3D modelling**. Desired as 3D explosion simulations reveal strong asymmetries.

Summary

- Supernovae are important sources of nucleosynthesis, but so far we have few quantitative results on production in individual sources and classes.
- Spectral modeling today done with NLTE over $\sim 10^4$ levels, e.g. with the SUMO code.
- Modelling of Type II SNe (from RSGs) indicate low/moderate amounts of oxygen ejected, and origin in low-mass stars ($M_{ZAMS} \sim 8 - 18\ M_\odot$).
- For superluminous Ic SNe, models indicate the highest O masses ($> 5\ M_\odot$) found in any SN so far. Must originate from very massive stars.
- A sample of CCSNe show Ni/Fe $\sim$ solar, but in a few cases higher. Follow-up analysis show high values requires high neutron excess of the fuel, only found in the silicon shell of the progenitor.
- Accurate atomic and molecular data crucial to being able to model SNe to the accuracy needed.

THANK YOU FOR LISTENING