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Supernova abundance analysis with NLTE spectral models

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Abstract. Supernovae provide environments with strong links to laboratory astrophysics. Diverse physical processes spanning from hot gas and semi-relativistic particles down to cold dusty clumps require extensive atomic data and understanding of processes across different physical regimes. The current status of modelling and analyzing supernova spectra is reviewed, with focus on recent results for diagnosing the production of oxygen and nickel.

Keywords. supernovae: general, line: formation, line: identification, radiative transfer

1. Introduction

Supernovae (SNe) come in two classes; core-collapse (CCSN) and thermonuclear (TNSN). The first type arises as the core of a massive star ($M_{ZAMS} \gtrsim 8\ M_{\odot}$) collapses to a neutron star or a black hole, leading to a blow-away of the mantle. The second type arises as a white dwarf accretes matter towards the Chandrasekhar limit, collapses and ignites explosive fusion burning of carbon and oxygen. By unit volume in the nearby Universe, the CCSN class is three times more common than the TNSN class.

These two types of explosions are believed to be responsible for the bulk production of all elements in the $\mathrm{Z} = 8 - 37$ range (oxygen to rubidium), and in addition make significant contribution to C and N ($\mathrm{Z} = 6$ and 7). Within this range CCSNe dominate the lower ($\mathrm{Z} = 6 - 13$, hydrostatic burning products) and upper ($\mathrm{Z} = 31 - 37$) range, whereas the mid range ($\mathrm{Z} = 14 - 30$, explosive burning products) have comparable contributions from both classes.

The $\mathrm{Z} = 31 - 37$ range has so far not been possible to probe due to the low abundances of these elements relative to others in the ejecta - no lines from these elements have been identified. But signatures from the hydrostatic ($\mathrm{Z} = 6 - 13$) and explosive ($\mathrm{Z} = 14 - 30$) categories are distinctly seen in SN spectra. Table 1 lists the 15 most common elements in the Universe, and the emission lines identified in supernova spectra. To get clear emission lines, one must wait until the "nebular phase" sets in after a few months. A diagnostic program aimed at determining more specifically which kind of supernova explosions produce which elements can give much important information about stellar evolution physics, the explosion mechanisms, and galactic chemical evolution. This text will give short review of supernova spectral modelling and the current status of diagnosing the production of two key elements; oxygen and nickel.

2. Spectral modelling

Figure 1 outlines the five main physical processes that need to be modelled in order to obtain theoretical predictions for the spectrum emitted by a supernova ejecta. The SUMO code (Jerkstrand *et al.* 2011, 2012) implements solution algorithms for each of these and iterates until convergence.

Table 1. The 15 most common elements in the Universe, their main production sites, and identified supernova emission lines. AGB stands for Asymptotic Giant Branch star.

Ab.	El.	Main source	Nebular lines seen in SNe
1	H	Big Bang	Many
2	He	Big Bang	He I 5016 Å, 7065 Å, 1.08 μm, 2.06 μm
3	O	CCSN	[O I] 5577 Å, [O I] 6300, 6364 Å, O I 7774 Å, O I 9263 Å + ..
4	C	AGB stars+CCSN	[C I] 8727 Å, 9824/9850 Å, 1.44 μm, CO lines
5	Fe	CCSN+TNSN	[Fe II] 7155 Å, 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 Å
9	Mg	CCSN	Mg I] 4571 Å, 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 Å, 1.93 μm, 6.6 μm, 10.7 μm, [Ni I] 3.1 μm
13	Ca	CCSN	[Ca II] 7300 Å, NIR triplet, Ca I 4200 Å
14	Al	CCSN	-
15	Na	CCSN	Na I 5890, 5896 Å, 1.14 μm

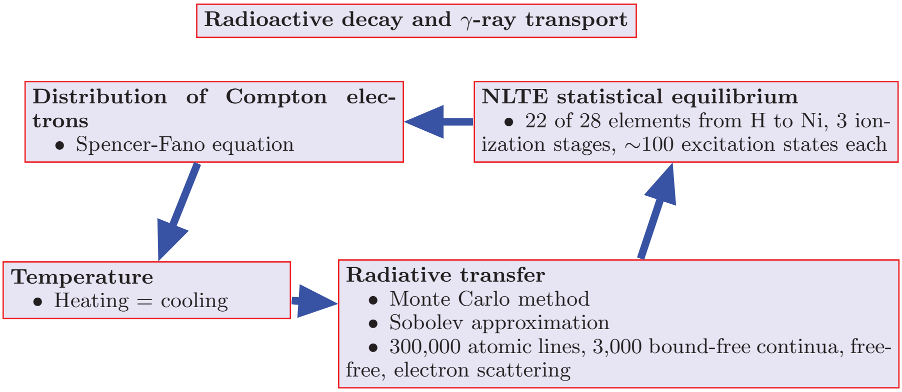

Figure 1. Overview of SUMO spectral modelling code.

Radioactivity. Radioactivity is the standard energy source that keeps the supernova emitting over longer period of time (months/years). After a few weeks, the internal energy deposited in the explosion will have been radiated away or converted to kinetic energy by adiabaic cooling, and a longer-lasting energy source is needed to keep the supernova bright. The most important isotopes to include in modelling are ^{56}Ni, ^{57}Ni, and ^{44}Ti (and their daughter nuclei).

Distribution of Compton electrons. The radioactive decay products create a population of high-energy electrons when they collide with the gas. It is the properties of this population that governs how the gas is heated, ionized and excited. This distribution is solved for using the technique of Kozma & Fransson (1992).

Temperature. Temperature is calculated by balancing heating with cooling, as such steady state can be shown to hold in the ejecta.

NLTE statistical equilibrium. The number density in the ejecta is well below the LTE limits after a few weeks, and level populations therefore need to be solved for through the rate equations (Jerkstrand 2017). SUMO solves for 22 elements, considering the first 3 ionization stages for each. Higher ionization states are not needed as the ejecta are quite neutral at nebular times.

Radiative transfer. While the ejecta become mostly optically thin in the continuum after a few weeks, line opacity remain for years or even decades. This line blocking redistributes energy in the spectrum from shorter to longer wavelengths. SUMO treats this process with a Monte Carlo method, with 300,000 lines plus continuum processes.

3. Results: oxygen

Oxygen is perhaps the most analyzed element from supernova nebular spectra. Its significance stems from several factors. It is the main nucleosynthetic product of core-collapse supernovae (and by all nucleosynthesis sources in the Universe after the Big Bang, making it the third most common element after H and He). Its production has a steep dependence on the mass of the star making it a good tracer for this important property. It has several strong lines in well-observed parts of the optical spectrum (5577, 6300/6364, 7774 Å), and these are also relatively unblended. The formation of the main line (6300/6364 Å) occurs in a relatively straightforward fashion by thermal collisional excitation.

In the last few years the first grids of models spanning over M_{ZAMS} (Zero-Age-Main-Sequence mass) have been produced, and allow any observed spectrum to be given a "best match" (Jerkstrand *et al.* 2012, 2014; Dessart *et al.* 2013). This has shown that standard stellar evolution/explosion models in the $10-20$ $M_{\odot}$ range reproduce observed Type II SN spectra quite well (Fig. 2). Further, at a more quantitative level the best matches are always below 17 $M_{\odot}$ (Jerkstrand *et al.* 2014, 2015b; de Jaeger *et al.* 2019), with the possible exception of SN 2015bs (Anderson *et al.* 2018). This seems to confirm the "red supergiant problem" that has emerged from the lack of any bright progenitors from the $17-30$ $M_{\odot}$ range (Smartt 2009, 2015).

Recently progress has also been made to better resolve and understand the low-mass end (Jerkstrand *et al.* 2018; Lisakov *et al.* 2018). About 1/3 of all CCSN should arise from $\sim 8-11$ $M_{\odot}$ stars, which are predicted to explode with low energy and small nucleosynthesis yields. The first detailed models from this range give good matches to the observed class of subluminous IIP SNe (Jerkstrand *et al.* 2018). The detailed nature of lines from C, O, Ni also show that all well observed events so far are CCSNe, with none matching predictions from electron-capture SNe. This also seems to be in line with recent developments in stellar evolution modelling where the mass range able to give such explosions is quite small (Doherty *et al.* 2015).

Larger oxygen yields (several solar masses) have been inferred in a few cases of rare stripped-envelope supernovae (Mazzali *et al.* 2001; Jerkstrand *et al.* 2017; Nicholl *et al.* 2019). However, the typical stripped-envelope supernova does not seem to eject more oxygen than hydrogen-rich SN (Jerkstrand *et al.* 2015; Morales-Garoffolo *et al.* 2015; Fremling *et al.* 2019; Prentice *et al.* 2019), with a typical yield being 0.5 $M_{\odot}$ in both classes.

4. Results: nickel

While radioactive nickel (^{56}Ni) is a key product made in both CCSNe and TNSNe, it is the neutron excess stable nuclei such as ^{58}Ni that hold key information about the fuel layer and the explosive burning. Nickel has only one distinct line in the optical - [Ni II] 7378 Å. Often this is blended/swamped by [Ca II] 7291, 7323 Å. However, SN 2012ec had a strong enough Ni II line that its luminosity could be clearly extracted (Jerkstrand *et al.* 2015b). It forms in a very similar manner to [Fe II] 7155 Å, and the ratio of these lines therefore becomes a quite robust diagnostic of the Ni/Fe ratio in the ejecta.

Estimates of this ratio in a set of CCSNe with good data show that two groups can be delineated - one where the Ni/Fe ratio is around solar, and one where it is around 3 times solar (Jerkstrand *et al.* 2015b). Although more data is needed to firmly establish these groups, a follow-up study on how the Ni/Fe ratio comes about shows that two

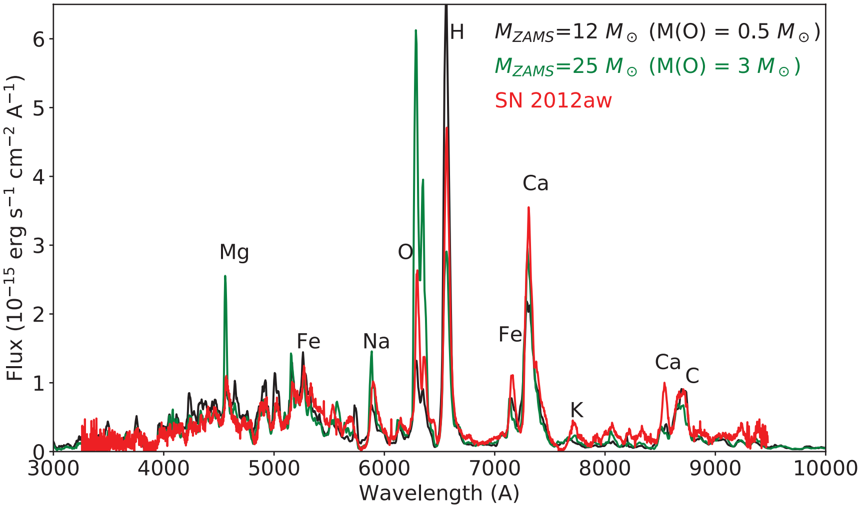

Figure 2. Type II supernova SN 2012aw (red) compared to two SUMO models (Jerkstrand *et al.* 2014) of 12 $M_\odot$ (green) and 25 $M_\odot$ (black) stars.

distinct groups are naturally formed depending on whether it is the O or Si layer in the progenitor that is the burned and ejected. In the former case, the neutron excess gives a Ni/Fe ratio close to solar, whereas in the latter, it gives about 3 times solar (Jerkstrand *et al.* 2015c). Application of the Jerkstrand *et al.* (2015b) method to further data have so far shown consistency with either the solar (Tomasella *et al.* 2018) or about 3 times solar value (Terreran *et al.* 2016).

As only CCSNe and TNSNe make (any significant) contribution to Fe and Ni, locking down the production in one of these channels also implies what the other one must produce. Recently studies of the same line in TNSNe have led to indications of a Ni/Fe ratio relatively close to solar also in Ia SNe (Maguire *et al.* 2018). Thus the current picture is that both classes on average make Ni/Fe ratios close to solar.

5. Discussion

In the context of laboratory astrophysics, the atomic data used in supernova spectral analysis comes into focus. The atomic data needed comes in seven categories, which for the current SUMO code in turn may be assessed as ‘satisfactory’, ‘intermediate’, or ’unsatisfactory’. In the first category, energy levels and A-values for the $Z = 1 - 30$ range are now probably of sufficient accuracy that errors in them are not the limiting factor in any of the key analyses. In the intermediate category one may put (thermal) collision strengths, photoionization cross sections, and recombination rates. These are generally extensive and of good quality but certainly additions and improvements are needed. As a concrete illustration, recently the collision strengths for Mg I were calculated with improved methods, and a direct factor 2 change in supernova model spectra could be illustrated (Barklem *et al.* 2017). An ‘unsatisfactory’ label one would put for non-thermal collision strengths and charge transfer. For most elements detailed non-thermal collision strengths are lacking, and the Bethe approximation (Bethe 1930) is used. For charge transfer, the most important reactions in SNe are metal-metal reactions, whereas most calculation are available for H/He-metal reactions.

Improvements on the atomic data would be desirable for both the latter categories. It is difficult to make any blanket statements on which kind of data is most desirable as this depends on the supernova type as well as the phase and observable of interest.

CCSNe are dominated by intermediate-mass elements like oxygen and carbon and charge transfer reactions between these have been shown to be important (Jerkstrand *et al.* 2011). For TNSNe the composition is dominated by iron-group elements and thermal collision strengths and photoionization cross sections for Fe, Co, Ni become important. For very late times for both classes, non-thermal processes become dominant and accurate cross sections for collisional ionization and excitation are needed.

References

Anderson, J. P., Dessart, L., Gutierrez, C. P., *et al.* 2018, *Nature Astron.*, 2, 574
Barklem, P., Osorio, Y., Fursa, D. V., *et al.* 2017, *A&A*, 606, A11
Bethe, H 1930, *AdP*, 397, 3, 325
de Jager, T., Zheng, W., Stahl, B. E., *et al.* 2019, *MNRAS*, 490, 2799
Dessart, L., Hillier, J., & Waldman, R. 2013, *MNRAS*, 433, 2
Doherty, C., Gil-Pons, P., Siess, L., *et al.* 2015, *MNRAS*, 446, 3
Fremling, C., Ko, H., Dugas, A. *et al.* 2019, *ApJL*, 878, 1
Mazzali, P., Nomoto, K., Patat. F., & Maeda, K. 2001, *ApJ*, 559, 2
Jerkstrand, A., Fransson, C., & Kozma C. 2011, *A&A*, 530, 45
Jerkstrand, A., Fransson, C., Maguire, K., *et al.* 2012, *A&A*, 546, 28
Jerkstrand, A., Smartt, S. J., Fraser, M., *et al.* 2014, *MNRAS*, 439, 4
Jerkstrand, A., Ergon. M., Smartt, S.J., *et al.* 2015a, *A&A*, 573, A12
Jerkstrand, A., Smartt, S. J., Sollerman, J., *et al.* 2015b, *MNRAS*, 448, 3
Jerkstrand, A., Timmes, F., Magkotsios., G., *et al.* 2015c, *ApJ*, 807, 1
Jerkstrand, A., Smartt, S.J., Inserra, C., *et al.* 2017, *ApJ*, 13, 23
Jerkstrand, A. 2017, *Handbook of Supernovae*, 795
Jerkstrand, A., Ertl, T., & Janka, T. 2018, *MNRAS*, 475, 1
Kozma, C. & Fransson, C. 1992, *ApJ*, 390, 602
Lisakov, S., Dessart, L., Hillier, J., *et al.* 2018, *MNRAS*, 473, 3
Morales-Garoffolo, A., Elias-Rosa, N., Bersten, M., *et al.* 2015, *MNRAS*, 454, 1
Maguire, K., Sim, S., A., Shingles, S., *et al.* 2018, *MNRAS*, 477, 3
Nicholl, M., Berger, E., Blanchard, P., *et al.* 2019, *ApJ*, 871, 1
Prentice, S. J., Ashall, C., James, P. A., *et al.* 2019, *MNRAS*, 485, 2
Smartt, S. J. 2009, *ARA&A*, 47, 1
Smartt, S. J. 2015, *PASA*, 32, 016
Terreran, G., Jerkstrand, A., Benetti, S., *et al.* 2016 *MNRAS*, 462, 1
Tomasella, L., Cappellaro, E., Pumo, M. L., *et al.* 2018 *MNRAS*, 475, 2