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H and He in stripped-envelope SNe – how much can be hidden?

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Abstract. H and He features in photospheric spectra have rarely been used to constrain the structure of Type IIb/Ib/Ic supernovae (SNe IIb/Ib/Ic). The lines have to be modelled with a detailed non-local-thermodynamic-equilibrium (NLTE) treatment, including effects uncommon in stars. Once this is done, however, one obtains valuable hints on the characteristics of progenitors and explosions (composition, explosion energy, ...). We have extended a radiative transfer code to compute synthetic spectra of SNe IIb, Ib and Ic. Here, we discuss our first larger set of models, focusing on the question: How much H/He can be hidden (i.e. remain undetected in photospheric spectra) in SNe Ib/Ic? For the SNe studied (relatively low $M_{\rm ej} = 1...3\ {\rm M}_\odot$), we find a limit of $M_{\rm He} \lesssim 0.1\ {\rm M}_\odot$ in SNe Ic (no unambiguous He lines). Stellar evolution models for single stars normally always yield higher masses. We suggest that low- or moderate-mass SNe Ic result from efficient envelope stripping in binaries. We propose similar studies on H/He in high-mass and extremely aspherical SNe, and observations covering the region of He I λ20581.

Keywords. supernovae: general, supernovae: individual (SN 2008ax, SN 1994I), techniques: spectroscopic, radiative transfer

1. Introduction

Establishing a solid mapping between the spectroscopic appearance of supernovae (SNe) and their physical properties (abundances, explosion energy, progenitor configuration) is a primary objective in SN science. It is achieved by radiative transfer simulations, yielding synthetic observables (e.g. Mazzali 2000; Kasen *et al.* 2004). SN and progenitor models can then be validated by comparison to observations.

In the field of stripped-envelope core-collapse SNe with He (Type IIb/Ib SNe), studies based on synthetic early-phase spectra have rarely been conducted (Utrobin 1996; Mazzali *et al.* 2008). Radiative transfer modelling of their atmospheres requires accurate non-local-thermal-equilibrium (NLTE) calculations to determine the state of the He-rich plasma in the SNe. The excitation/ionisation pattern in this case is strongly influenced by collisions with fast electrons, which result from Compton processes with γ-rays from the decay of ^{56}Ni and ^{56}Co (Lucy 1991). We have enabled a well-established SN spectrum synthesis code (Lucy 1999; Mazzali 2000) to compute the relevant collision rates and solve the stationary NLTE rate equations (Hachinger *et al.* 2012).

Using the upgraded code, we calculated spectra for a sequence of Type IIb/Ib/Ic SNe (SNe IIb/Ib/Ic), varying the envelope mass. In this way, we can determine the mass a (partially stripped) H- or He-envelope of a SN must have for the respective lines to show up. We discuss implications for progenitor models and for future studies on SN spectra.

2. Models

Employing the "abundance tomography" technique (Stehle *et al.* 2005) to infer the abundance stratification, we produced (Hachinger *et al.* 2012) optimum ejecta models for the SN IIb 2008ax (e.g. Chornock *et al.* 2011; Taubenberger *et al.* 2011) and the SN Ic 1994I (e.g. Iwamoto *et al.* 1994; Filippenko *et al.* 1995; Sauer *et al.* 2006). Our models use the density profile of the explosion models "4H47" (Shigeyama *et al.* 1994) and "CO21" (Iwamoto *et al.* 1994), which are based on the same stellar core (with a He/H envelope and without). The synthetic spectra match the observations between 16 d and 41 d past explosion. Furthermore, using the algorithm of Cappellaro *et al.* (1997), we were able to show that the models reproduce the observed bolometric light curves.

A "SN Ic → SN IIb" model sequence (with 40 steps) was obtained from these models by constructing (approximate) "transitional" density and abundance profiles (Hachinger *et al.* 2012). These represent explosions of stars with the same Fe/Si/O/C core, differing only in the envelope. The $E_{\rm kin}$ of all these models is by construction 10^{51} erg, as inferred

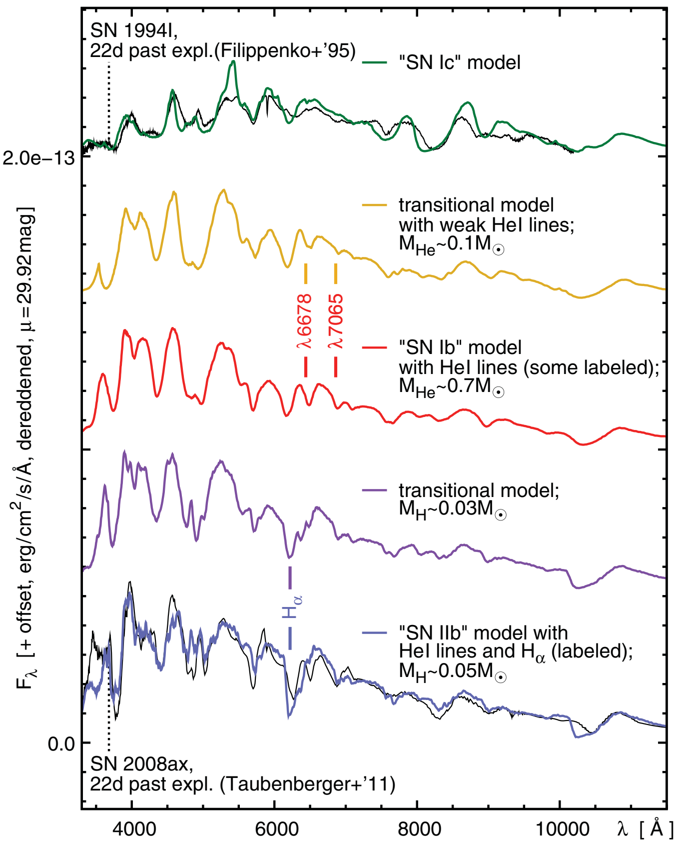

Figure 1. SN Ic → SN IIb sequence of spectral models (coloured/grey graphs) at an epoch of 22 d after explosion. The SN Ic/IIb models have an abundance structure optimised to match observed SNe (black graphs). Identifiers are given for the H/He lines mentioned in the text.

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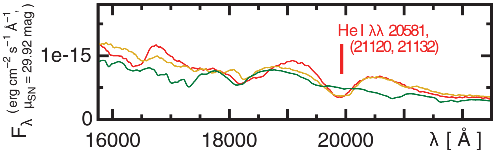

Figure 2. The region around 20000 Å in our SN Ib/c model spectra, the optical part of which is shown in Figure 1. The deepest λ20581 feature is found in the SN Ib model (red), a medium depth in the transitional model (yellow), and no feature in the SN Ic model (green).

for the reference SNe (1994I and 2008ax). The chemical structure of the sequence models was derived from the SN 08ax and 94I models by interpolation at each enclosed M.

Some spectra of the sequence, for an epoch of 22 d after explosion, are shown in Figure 1. We plot the "anchor" models for SN 1994I and SN 2008ax with the respective data, and a few interesting intermediate models.

Going from the SN Ic/1994I model (Fig. 1, top graph) towards more He-rich models (graphs below), one can see that for a He envelope mass of

$$M(\mathrm{He})_{\mathrm{SNIc/Ib}} = 0.1\ \mathrm{M}_\odot,$$

clear lines appear in the optical spectrum ($\lambda\lambda$6678, 7065; these features have sufficiently low contamination by other species). A typical SN Ib is obtained for $M(\mathrm{He}) \sim 0.7\ \mathrm{M}_\odot$.

Similarly, for $M(\mathrm{H})_{\mathrm{SNIb/IIb}} \sim 0.03\ \mathrm{M}_\odot$, the H$\alpha$ feature gets pronounced. For $M(\mathrm{H}) \sim 0.05\ \mathrm{M}_\odot$, we obtain a typical SN IIb spectrum (Fig. 1, bottom). Note that smaller $M(\mathrm{H})$ will be detectable in earlier spectra (cf. Arcavi *et al.* 2011 & questions).

3. Discussion and conclusions

From our sequence of synthetic spectra, we have derived limits on H and He in SNe IIb/Ib/Ic with ejecta masses from $\sim 3\ \mathrm{M}_\odot$ (in 4H47/SN 2008ax) to $\sim 1\ \mathrm{M}_\odot$ (in CO21/SN 1994I). We find that SNe Ib have $M(\mathrm{H}) \lesssim 0.03\ \mathrm{M}_\odot$, and SNe Ic $M(\mathrm{He}) \lesssim 0.1\ \mathrm{M}_\odot$. While we have focused on the optical, another excellent diagnostic on He is the λ20581 feature (Fig. 2). The well-isolated line reacts very sensitively on the He abundances (as it is strong, but not completely saturated). More observations of He I λ20581 in SNe Ib/Ic would allow for constraining He abundances with unprecedented accuracy.

It is interesting to compare the limits we have derived from the optical spectra with results from stellar evolution calculations for progenitors (Georgy *et al.* 2009; Yoon *et al.* 2010). Stellar evolution studies (involving binarity or not) generally succeed in explaining envelopes as in our SN IIb and SN Ib models, but not the low He masses we infer for SNe Ic. The models presented by Georgy *et al.* (2009), which are single Wolf-Rayet stars, always have $\gtrsim 0.3\ \mathrm{M}_\odot$ of He. In order to explain the total SN Ic rate with their progenitors, they must allow for He masses up to $0.6\ \mathrm{M}_\odot$ in SNe Ic. Also Yoon *et al.* (2010), who simulated binaries with one to three phases of "case A" or "case B" mass transfer, produce only a small number of progenitors with $M(\mathrm{He}) < 0.5\ \mathrm{M}_\odot$. Eldridge *et al.* (2011) find a somewhat larger rate of progenitors with low $M(\mathrm{He})$, but it is unclear whether this suffices. "Exotic" models may be needed to explain SN 1994I-like, low-mass Ic's. Iwamoto *et al.* (1994) and Nomoto *et al.* (1994) proposed for this SN a binary scenario in which the companion is a neutron star in the last mass transfer phase.

It has to be checked whether more He can be hidden in the ejecta of more massive or strongly asymmetric SNe Ic. Accurately constraining the He content of these objects may also help to understand what distinguishes energetic SNe Ic associated with a GRB from similar objects without a GRB (cf. Mazzali *et al.* 2008). While we are further developing our models, we hope that more observations of SNe Ib/Ic (with good time coverage up to 50 d after explosion, and spectra covering the 2μ region) will become available.

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Discussion

Chornock: Why was the first epoch chosen for fitting the models at 16 d? It seems to me that, if you want to model trace amounts of H and He in the outer envelope, you might want to choose an epoch when the photosphere is in the outermost layers.

Hachinger: The epochs, 16 d to 41 d after explosion, were selected so as to achieve an optimum sensitivity on He, as the He limit seemed more critical. At 16 d there is quite some sensitivity on H, but stricter limits might indeed be derived from earlier spectra.

Gal-Yam: A comment: The result suggesting very little He in SN Ic progenitors is supported by the non-detection in shock-breakout observations by Corsi *et al.* (2012) and Sauer *et al.* (2006) (SN 1994I).

Hachinger: Thanks! This independent evidence is very interesting!