

Modelling the spectral evolution of Supernovae.

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ABSTRACT

We present JEKYLL, a new code for modelling of SN spectra and lightcurves based on Monte-Carlo (MC) techniques for the radiative transfer. The code assumes spherical symmetry, homologous expansion and steady state for the matter, but is otherwise capable of solving the time-dependent radiative transfer problem in non-local-thermodynamic-equilibrium (NLTE). The method used was introduced in a series of papers by Leon Lucy, and we have extended it to include non-thermal excitation and ionization as well as charge-transfer and two-photon processes. Macroscopic mixing of the material, known to occur in the SN explosion, is taken into account in a statistical sense using a method introduced by Anders Jerkstrand. To save computational power we use a diffusion-approximation solver in the inner region, where the radiation field is thermalized. Except for a description of JEKYLL, we provide comparisons with the ARTIS and SUMO codes in the photospheric and nebular phase, respectively, which show a good agreement in the calculated spectra as well as the state of the gas. We also provide an application to Type IIb SNe, by calculating the early evolution for a model previously found to give a good match to SN 2011dh in the nebular phase. A thorough comparison to observations of SN 2011dh is made, and we find that both spectra and lightcurves are reasonably well reproduced, although there are also some clear differences. We also find that the model reproduce many general features of Type IIb SNe that have previously been noted in observational studies. Comparing to results where NLTE was partly switched off as well as to previous results with the LTE-based HYDE code, we see strong effects of NLTE even on the bolometric lightcurve. This highlights the needs for full NLTE calculations when simulating the spectra and lightcurves of SNe.

Key words. supernovae: general

1. Introduction

Modelling the spectral evolution and lightcurves of supernovae (SNe) is crucial for our understanding these phenomena, and much effort has been put into this during the last 50 years. To achieve realistic results local thermodynamical equilibrium (LTE) can generally not be assumed, and the full frequency-dependent, non-LTE (NLTE) problem has to be solved. Several paths exist and here we follow the one outlined in a series of papers by Lucy (2002, 2003, 2005, hereafter L02, L03, L05). Using this method, the radiative transfer is solved by a Monte-Carlo (MC) calculation, which is alternated with a NLTE solution for the matter until convergence is achieved (Λ -iteration). Basic tests were performed in the original papers, and a simplified version of the method, assuming LTE for the population of excited states, has been implemented in the code ARTIS (Kromer & Sim 2009, hereafter K09). Here we present JEKYLL, a C++ based code which implements the full NLTE-version of the method, extended to include also non-thermal excitation and ionization as well as charge-transfer and two-photon processes. These extensions are particularly important for modelling in the nebular phase, and for the calculation of the non-thermal rates we use the method developed by Kozma & Fransson (1992, hereafter KF92). Contrary to ARTIS, the initial version of JEKYLL is restricted to a spherical symmetric geometry, although the MC radiative transfer is performed in 3-D. In the paper, we present comparisons with ARTIS as well as the steady-state code SUMO (Jerkstrand et al. 2011, hereafter J11) aimed for the nebular phase. SUMO has NLTE-capabilities similar to JEKYLL, and together these two comparisons provide a critical test of most of the functionality of JEKYLL.

Type IIb SNe are thought to originate from stars that have lost most, but not all of their hydrogen envelope. Except for the prototypical Type IIb SN 1993J, the most well-observed Type IIb SN is 2011dh, for which we presented observations and modelling of the lightcurves in Ergon et al. (2014, 2015, hereafter E14, E15), as well as modelling of nebular spectra in Jerkstrand et al. (2015, hereafter J15). The modelling suggested a mass of $\sim 12 M_{\odot}$ for the progenitor, a conclusion supported by observations of the star in pre-explosion images (Maund et al. 2011). As stellar winds for stars of this mass seem too low to expel the hydrogen envelope this suggests a binary origin, where the hydrogen envelope was lost through interaction with a companion star. A similar conclusion, based on modelling of the SN, pre-explosion observations of the progenitor star, as well as a likely post-explosion detection of the companion star, applies to SN 1993J. It is therefore of great interest to further explore the preferred $12 M_{\odot}$ model presented in J15, evolved through the nebular phase using SUMO, and compared to the observed spectra and lightcurves of SN 2011dh in J15 and E15, respectively. This model was also evolved through the early phase using the hydrodynamical, LTE-based code HYDE in E15, allowing a comparison of the bolometric lightcurve with observations. Using JEKYLL we are able to calculate the early spectral evolution, as well as the broadband and bolometric lightcurves in much greater realism, and compare to observations as well as to the results obtained with HYDE.

The paper is organized as follows. In Sect. 2 we discuss the underlying physical problem, and in Sect. 3 we describe the method used to solve this problem and the implementation of the code. In Sect. 4 we provide comparisons of JEKYLL to the ARTIS and SUMO codes. In Sect. 5 we apply the code to Type

Ib SNe, calculate the early spectral evolution for the preferred J15 model, and discuss and compare the results to observations of SN 2011dh. Finally, in Sect. 6 we conclude and summarize the paper.

2. Physics

The general physical problem addressed is the time-evolution of the radiation field and the state of the matter given the dynamical constraint of homologous expansion, and might be referred to as a radiation-thermodynamical problem. If the radiation field and the matter are in local thermodynamical equilibrium (LTE) this is simplified to a one-parameter (i.e the temperature) problem, and may be easily solved. Otherwise, we are in the non-LTE (NLTE) regime, and the number of parameters as well as the complexity of the problem increase drastically.

As is often done, we solve for the radiation field and state of the matter separately, and the problem is split into a radiative transfer and a thermodynamical part. The coupling, provided by radiation-matter interactions, is enforced through Λ -iterations, where the state of the matter and the radiation field are alternately and iteratively determined from each other. The Λ -iteration concept is at the heart of the method, and in Sect. 2.1 we provide some background and discuss the somewhat different meaning it has in traditional and MC based methods.

The state of the matter can be split into a dynamical and thermodynamical part, where the former is trivially given by $\rho = \rho_0 (t/t_0)^3$ and $v = r/t$ through the constraint of homologous expansion. The thermodynamical part is given by the temperature, and the populations of the energy states of the ions, which are solved for using the thermal energy equation and the NLTE rate equations, respectively. To simplify we assume steady state, which is motivated if the thermodynamical time-scale is much smaller than the dynamical time-scale.

The radiation field is given by the specific intensity, which is solved for using the MC method outlined by L02, L03 and L05, and discussed in Sect. 3.3. In a traditional code like CMFGEN the specific intensity is solved for using the radiative transfer equation, whereas in a MC based code like JEKYLL, the radiative transfer is treated explicitly by propagating radiation packets which interacts with the matter through absorption, emission and scattering. The different radiation-matter interactions supported are discussed in Sect. 2.4.

In addition, radioactive decays emit high-energy photons or leptons, which give rise to a non-thermal electron distribution. Through collisions, these electrons contribute to the heating of the electron gas and the excitation and ionization of the ions. The problem may be broken up into two parts; deposition of the radioactive decay energy, and the partitioning of this energy into non-thermal heating, ionization and excitation.

2.1. Λ -iterations and convergence

In terms of the Λ -operator the radiative transfer equation may be written as $I = \Lambda[S]$, where I is the intensity and S the source-function. If the source function depends on the intensity, as in the case of scattering, solving the problem requires inverting the Λ -operator. This is typically a costly operation, and we may instead try an iterative procedure called Λ -iteration. In its original form an improved estimate of the intensity is then determined using the previous estimate of the source-function, i.e. $I_{i+1} = \Lambda[S_i]$. However, as has been extensively discussed in the literature, this method may converge extremely slowly if the source function

is dominated by scattering, as the non-local coupling introduced only propagates one mean-free path in each iteration. This may be solved by splitting the Λ -operator in two parts, one acting on the current iterate and one acting on the previous iterate, i.e. $I_{i+1} = \Lambda^*[S_{i+1}] + (\Lambda - \Lambda^*)[S_i]$. With an appropriate choice of Λ^* , e.g the local part of Λ , which is trivial to invert and still close to Λ , convergence could be accelerated, and the procedure is therefore known as accelerated Λ -iteration.

It is important to realize that MC based Λ -iterations, unlike the traditional ones, do not suffer from slow convergence in the case of a scattering dominated source-function. The reason for this is that the MC scattering emissivity depends directly on the current iterate of the radiation field. Actually, such a Λ -iteration is analogous to an accelerated Λ -iteration and may be written as $I_{i+1} = \Lambda^*[I_{i+1}, \bar{n}_i, T_i] + (\Lambda - \Lambda^*)[I_i, \bar{n}_i, T_i]$, where Λ^* operates on the current iterate of the radiation field and \bar{n} is the ion population vector. Enforcing the constraints of thermal and statistical equilibrium on the MC calculation, introduces a direct (but approximate) dependence of all MC emissivities on the current iterate of the radiation field, which further improves the Λ^* -operator. This idea is central for the method outlined by L02-L05, and as demonstrated in L03, Λ -iterations based on this operator splitting has excellent convergence properties.

2.2. Statistical equilibrium

To determine the populations of the energy states of the ions, the NLTE rate equations need to be solved. Assuming steady state, these equations simplify to the equations of statistical equilibrium, where the rates of transitions in and out of each state are in equilibrium. The statistical equilibrium equation for level i of ion I may be written

$$\sum_{J=I\pm 1} \Lambda_{J,i \rightarrow I,i}^{\text{BF}} n_{J,j} + \sum_{j \neq i} \Lambda_{I,j \rightarrow i}^{\text{BB}} n_{I,j} = \left(\sum_{J=I\pm 1} \Lambda_{I,i \rightarrow J,j}^{\text{BF}} + \sum_{j \neq i} \Lambda_{I,i \rightarrow j}^{\text{BB}} \right) n_{I,i} \quad (1)$$

where Λ is the transition rate (per particle) for bound-free (superscript BF) and bound-bound (superscript BB) transitions. Transitions may be caused by absorption/emission of photons (Sect. 2.4), or by collisions involving ions and thermal (Sect. 2.5) or non-thermal (Sect 2.6.1) electrons.

2.3. Thermal equilibrium

To determine the thermal state of the gas the thermal energy equation needs to be solved. Assuming steady state, this equation simplifies to the equation of thermal equilibrium, where the heating and cooling of the gas are in equilibrium. The thermal equilibrium equation may be written

$$\sum_{J=I\pm 1} g_{I,i \rightarrow J,j}^{\text{BF}}(T) n_{I,i} + \sum_{i \neq j} g_{I,i \rightarrow j}^{\text{BB}}(T) n_{I,i} + \sum g_I^{\text{FF}}(T) n_{I,i} = H^{\text{NT}} \quad (2)$$

where $g = h - c$ is the net heating rate (per particle) for bound-free (superscript BF), bound-bound (superscript BB) and free-free (superscript FF) transitions, and H^{NT} is the heating rate by non-thermal collisions. Heating/cooling may arise through absorption/emission of photons (Sect. 2.4), or through collisions involving ions and thermal (Sect. 2.5) or non-thermal (Sect 2.6.1) electrons.

2.4. Radiation-matter interactions

In radiation-matter interactions, the radiation field and the matter (electrons and ions) exchange energy through absorption and emission of photons. Except for electron scattering, which is assumed to be coherent and isotropic in the co-moving frame (of the ejecta), and given by the Thomson cross-section, JEKYLL supports the following interactions.

Bound-bound Through detailed balance, the excitation and de-excitation rates are related and determined by a single quantity, e.g. the spontaneous emission coefficient. We assume that the Sobolev approximation applies, which is appropriate when expansion broadening dominates. Expressions for the Sobolev optical depth as well as the transition rates are given in L02. In addition, we also support de-excitation through two-photon emission for bound-bound transitions otherwise radiatively forbidden.

Bound-free Through detailed balance, the ionization and recombination rates are related and determined by a single quantity, e.g. the photoionization cross-section. In bound-free transitions, the energy absorbed/emitted goes partly into ionization/recombination of the ion, and partly into heating/cooling of the electron gas. Expressions for the opacity, emissivity, transition rates and heating/cooling rates are given in L03.

Free-free Refers to Bremsstrahlung, and assuming thermal matter, the opacity and emissivity are related through Kirchoff's law. In free-free interactions, the energy of the photons absorbed/emitted goes solely into heating/cooling of the electron gas. Expressions for the opacity, emissivity, and heating/cooling rates are given in L03.

2.5. Matter-matter interactions

In matter-matter interactions, electrons and ions exchange energy through collisions. The collisions heat/cool the electron gas and result in bound-bound or bound-free transitions of the ions. Except for non-thermal collisions, which are discussed in Sect. 2.6.2, JEKYLL supports the following interactions.

Bound-bound and bound-free Assuming detailed balance, the collisional excitation and de-excitation rates can be related and expressed in terms of a single quantity, e.g. the collisional strength. Expressions for the transition rates, and heating/cooling rates are given in L03.

Charge-transfer In collisions involving two ions, electrons may be transferred from one ion to another. This process is called charge-transfer and may be viewed as a recombination followed by a ionization. The charge transfer rates may be expressed in terms of a charge-transfer coefficient that depends only on the temperature as

$$\begin{aligned} R_{\bar{I},\bar{J}\rightarrow\bar{U},\bar{L}} &= \alpha_{\bar{I},\bar{J}\rightarrow\bar{U},\bar{L}}(T) n_{\bar{I}} n_{\bar{J}} \\ R_{\bar{U},\bar{L}\rightarrow\bar{I},\bar{J}} &= \frac{\alpha_{\bar{I},\bar{J}\rightarrow\bar{U},\bar{L}}(T)}{\phi_{\bar{I},\bar{J},\bar{U},\bar{L}}(T)} n_{\bar{U}} n_{\bar{L}} \end{aligned} \quad (3)$$

where $\phi_{\bar{I},\bar{J},\bar{U},\bar{L}}(T) = (n_{\bar{I}}^* n_{\bar{J}}^*) / (n_{\bar{U}}^* n_{\bar{L}}^*)$, the asterisk indicates the LTE value and $\bar{I} = (I, i)$ is an index vector specifying level I

of ion i . The energy difference between the initial and final state of the process give rise to heating or cooling of the electron gas with a rate given by $\alpha_{\bar{I},\bar{J}\rightarrow\bar{U},\bar{L}} (\chi_{\bar{L},\bar{I}} - \chi_{\bar{J},\bar{U}})$.

2.6. Radioactive decays

2.6.1. Energy deposition

The energy released in the radioactive decays is carried by high-energy photons and leptons which deposit their energy in the ejecta mainly through Compton scattering on free and bound electrons. Although a detailed calculation is preferred, we use effective grey opacities determined through such calculations. We support the decay chains $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$, $^{57}\text{Ni} \rightarrow ^{57}\text{Co} \rightarrow ^{57}\text{Fe}$ and $^{44}\text{Ti} \rightarrow ^{44}\text{Sc} \rightarrow ^{44}\text{Ca}$, which are the most important for core-collapse SNe. For these decays we adopt the same effective grey γ -ray opacities, life-times and energies as in J11, and assume that the positrons emitted are locally absorbed.

2.6.2. Energy partition

Through a cascade of collisions the deposited energy gives rise to a high-energy tail on the otherwise Maxwellian electron distribution. The shape of the non-thermal electron distribution and the fractions of the energy going into heating, excitation and ionization through non-thermal collisions can be calculated by solving the Spencer-Fano equation (Boltzman equation for electrons). This problem was solved by KF92 and for a further discussion we refer to this paper.

3. Method and implementation

Given the physical problem, we know describe the methods used to solve it, and provide an outline of how the code is constructed. Except for the non-thermal solver, the code is written in C++, and the description therefore tends to reflect the object oriented structure of the code. The code is parallelized on a hybrid process (MPI) and thread (open MP) level.

The SN ejecta is represented by a spatial grid of cells holding the local state of the matter and the radiation field. Although mostly geometry independent, the current version only supports spherically symmetric cells. To determine the state of the matter, JEKYLL provides several solvers with different levels of approximation (e.g. LTE and NLTE), and to determine the radiation field it provides a MC solver based on the method by L02-L05. As discussed, through Λ -iterations the matter and the radiation field are alternately determined from each other, and the procedure is terminated when convergence is achieved. JEKYLL also provides a diffusion solver, intended for use at high optical depths where the matter and radiation field may be assumed to be in LTE. JEKYLL may be configured to run in steady-state or time-dependent mode, although the latter only applies to the radiative transfer. Steady-state breaks down if the diffusion time is large, and is therefore best suited for modelling in the nebular phase, or of the SN atmosphere in the photospheric phase.

3.1. Grid

The grid represents the SN ejecta and is spatially divided into a number of cells. If macroscopic mixing is used, the cells may be further divided into compositional zones, geometrically realized as virtual cells. The grid provides functions to load the ejecta model, to load and save the state, as well as to export a broad range of derived quantities (e.g. opacities).

3.1.1. Cells

The cells hold the local state of the matter and the radiation field, and provide functions for the solvers to calculate derived quantities like opacities/emissivities and transition rates based on the local state and the atomic data. The local state of the matter is represented by the density, the temperature, the abundances, and the number fractions of ionized and excited states. The local state of the radiation field is represented by the specific mean intensity, which is estimated and updated by the MC solver based on packet statistics following the method outlined by L03. In addition, JEKYLL supports simplified radiation field models based on pure or diluted blackbody radiation, as well as on the continuum source-function. The latter is intended for use in ground-state continua of abundant species, which typically have high optical depths and are dominating the source-functions.

3.1.2. Virtual cells

JEKYLL implements the concept of virtual cells, introduced by J11 to account for macroscopic mixing on a grid otherwise spherically symmetric. Each cell may be divided into zones occupying some fraction (filling factor) of the cell volume, and otherwise geometrically unspecified. These zones may have different densities and compositions, and the state is solved for separately by the matter-state solver. With respect to the MC-solver the zones are represented by virtual cells differing only in a geometrical and statistical sense. The virtual cells are spherical, have a size corresponding to some number of clumps, and their location are randomly drawn during the MC radiative transfer based on their size and the zone filling factor.

3.2. Atomic data

Once converted to the JEKYLL format, any set of atomic data may be loaded from file. The data is organized in a hierarchical structure of atoms, their isotopes and ions, and the bound states of the ions. Each ion holds a list of bound-bound transitions, and each atom holds a list of bound-free transitions. The atomic data also contains an (optional) list of charge-transfer reactions, which are mapped on two bound-free transitions, one recombination and one ionization. The specific atomic data used for the comparisons in Sects. 4.1 and 4.2 and for the application to Type IIb SNe in Sect. 5 are discussed separately in these sections.

3.3. MC radiative transfer solver

The MC radiative transfer solver determines the radiation field, and is based on the method outlined in L02-L03. The radiation field is represented by packets (Sect. 3.3.1), which are propagated on the grid (Sect. 3.3.2) and interact with the matter (Sect. 3.3.3). The method has been extended to include non-thermal ionizations and excitations as well as charge-transfer and two-photon processes. In addition, we introduce an alternative, more efficient way to sample the emission frequency (Sect. 3.3.4), and a method to control the sampling of the radiation field (Sect. 3.3.5). Although we explain the basics, we refer L02-L03 for the details of the original method.

3.3.1. Packets

The radiation field is represented by packets, defined by their energy, frequency, position and direction. Following L03 and K09, we classify these as r-, i-, k- and g-packets, but further intro-

duce e-packets to handle non-thermal processes. Freely propagating photons are represented by r-packets, and upon absorption they may be converted into i- and k-packets, representing ionization/excitation and thermal energy, respectively. The g-packets are similar to the r-packets, but represent the γ -rays (or leptons) emitted in the radioactive decays, which are converted into e-packets upon absorption, and further into i- or k-packets once one of the heating, ionization or excitation channels has been drawn. Eventually, i- and k-packets are always converted into r-packets and re-emitted.

Depending on the configuration, new r-packets may be injected into the MC calculation by sampling of the intensity (in the cells) or luminosity (at the borders) of the radiation field, and new g-packets by sampling of the γ -ray (or lepton) emissivity.

3.3.2. Propagation

When the r- and g-packets are propagated they undergo physical (radiation-matter interactions) and geometrical (border crossings) events. After each event, a random optical depth for the next physical event is drawn as $\tau = -\ln z$, and the packet is propagated until the accumulated optical depth exceeds this value or a geometrical event occurs. Note that line-absorption may only occur at the resonant distances, and the (Sobolev) line-opacity may be regarded as a delta-function. In the case of a physical event, the packet is processed as described in Sect. 3.3.3, and in either case propagation continues as described above. Note, that in the case of g-packets we use effective grey opacities (Sect 2.6.2), which differs from the more detailed procedure by L05. The r- and g-packets leave the MC calculation by escaping through the outer border, where the r-packets are summed and binned to build the observed spectrum.

If the packet enters a cell divided into compositional zones (Sect. 3.1.2), a randomly oriented virtual cell is drawn based on the filling factor of the corresponding zone. As long as the packet remains in the cell, the distance to the next geometrical event is given by the size and the orientation of the virtual cell, and at each border crossing the procedure is repeated.

3.3.3. Interactions

Once the packet has been absorbed, a specific interaction with the matter is drawn based on the opacities. In the case of electron scattering, the frequency does not change, and the packet is just re-emitted. Otherwise, an emission frequency is drawn using the macro-atom method described by L02 and L03, which enforce the constraints of thermal and statistical equilibrium on the MC calculation. Below we provide a summary of the method and describe the extensions made for non-thermal, charge-transfer and two-photon processes. Before re-emission of the packet a new direction is drawn from an isotropic distribution.

Original method In bound-bound absorptions radiative energy is converted into excitation energy, and the r-packets are converted to i-packets. In free-free absorptions radiative energy is converted into thermal energy, and the r-packets are converted into k-packets. However, in bound-free absorptions radiative energy is partitioned into both ionization and thermal energy, and the r-packets are converted into either i- or k-packets based on the partitioning of the energy. The i-packets activate the macro-atom state-machine, involving transitions between all bound states of the specie, in turn de-activated by the choice of a radiative or collisional de-excitation. Radiative de-excitations

correspond to re-emission of the absorbed energy, the packet is converted back into a r-packet and a new frequency drawn based on the transition. Collisional de-excitations correspond to conversion of the ionization/excitation energy into thermal energy, and the packet is converted into a k-packet. Based on the radiative and collisional cooling rates, k-packets are either converted into r-packets and re-emitted, or converted back into i-packets, in which case a new macro-atom state-machine is activated by a collisional excitation.

Non-thermal processes Upon absorption, a g-packet is converted into an e-packet, representing the energy of the non-thermal electrons. Conversion into either k- or i-packets is then drawn based on the non-thermal heating, excitation and ionization rates. Similarly, in the case of an i-packet the macro-atom state-machine is invoked by a non-thermal transition drawn based on the non-thermal excitation and ionization rates. The macro-atom state-machine is modified by adding the probabilities for non-thermal transitions, which are always internal.

Charge-transfer processes The macro-atom state-machine is modified by adding the probabilities for the corresponding ionization and recombination. Deactivation of the macro-atom state-machine through a charge-transfer recombination results in either re-activation through the corresponding ionization or, if the reaction is exo-thermic, in the conversion of the i-packet into a k-packet based on the energy released. Correspondingly, if the reaction is endo-thermic, k-packets may be transformed into i-packets based on the energy absorbed, and the macro-atom state-machine invoked by the corresponding ionization.

Two-photon processes The macro-atom state-machine is modified by adding the probabilities for (bound-bound) two-photon transitions. Such transitions might be internal or de-activating, and in the latter case the emission frequency is drawn from the provided two-photon frequency distribution.

3.3.4. Markov-chain solution to the state-machine

A problem with the macro-atom method is that the number of transitions in the state-machine may become very large. This is particularly true when the collisional rates are high, causing the state-machine to bounce back and forth between macro-atoms and the thermal pool. To avoid this we use Markov-chain theory to calculate the probabilities to escape the state-machine by a de-activating transition. This approach can be applied to macro-atoms, or to the complete state-machine, consisting of all macro-atoms and the thermal pool. According to Markov-chain theory the average time spent in state i , given that the machine is invoked in state j , specified by the matrix $S_{i,j}$, can be calculated from the matrix $P_{i,j}$, containing the probabilities for internal transitions from state i to state j , through the relation $S^{-1} = P - I$. Knowing S , we may proceed to the state from which the machine will de-activate by a single draw, and once there, we may draw the de-activating transition from their (normalized) probabilities. This is implemented as two look-up tables for each bound state, one containing (a row of) S , and one containing the (normalized) de-activating transition probabilities.

Applied to the complete state-machine, the matrix S has the size of the number of all bound states for all species plus one (the thermal pool), and the computational time to invert the matrix is a potential problem. This may be circumvented by split-

ting the state-machine into a top-level one, involving the thermal pool and all atoms, and an atom-level one involving the bound states of the atoms. The procedure is similar to what is described above, but the computational time to invert the top-level and atom-level S -matrices is much less than for the complete S -matrix.

3.3.5. Controlling the sampling of the radiation field

Another problem with the original method is that there is no (or limited) control of the number of packets as a function of frequency, time and space. This may result in too few packets, leading to noise in the radiation field estimators, or too many, leading to unnecessary computational effort. To solve this we introduce a method for continuous re-sampling of the packets by letting their energy vary as a function frequency, space and time. This breaks the indivisibility requirement and, as we will see, the indestructibility (energy conservation) requirement has to be modified to apply in an average sense.

A set of sampling regions (bounded in frequency, space and time) is defined, and each of these is assigned a packet energy. When packets cross the borders between sampling regions their energy is adjusted to that of the destination region. To maintain the rate of energy flowing across the borders, the rate of packets flowing across the borders has to be adjusted with the ratio of the packet energies in the source and destination regions (F). This is achieved by adjusting all emission rates with $1/F$ and introduce a fictitious "emission" opacity (κ_E) corresponding to the total adjusted emission rate (which may be higher or lower than the original one). Although the basic idea is simple, the actual implementation is complicated by the way the emission frequency is drawn in the macro-atom method.

Replacing κ with $\max(\kappa, \kappa_E)$, packets are selected for either absorption, emission or both. The packet is absorbed with probability $\max(\kappa/\kappa_E, 1)$ and emitted with probability $\max(\kappa_E/\kappa, 1)$. If the packet is absorbed but not emitted it is terminated, and if the packet is emitted but not absorbed a child packet is created. Otherwise the transition is handled as described above (which also recovers the normal behaviour if $\kappa = \kappa_E$). As is possible to show, this gives the correct (average) energy flows in and out of each sampling region. At spatial and temporal boundary crossings the packets are either split into F child packets (if $F > 1$) or terminated with probability $1 - 1/F$ (if $F < 1$).

3.4. Matter state solvers

To determine the state of the matter, JEKYLL provides the NLTE solver, as well as the more approximate LTE and nebular solvers. It also provides an option to mix these solvers, e.g. by using the NLTE solver for the ionization and the LTE solver for the excitation, in a manner similar to what is done in ARTIS. In addition, JEKYLL provides a solver to determine the non-thermal electron distribution, used by the NLTE solver.

3.4.1. LTE solver

The LTE solver determines the state of the matter assuming that LTE applies. The populations of ionized and excited states are calculated using the Saha ionization and Boltzman excitation equations, respectively. The temperature may be set to the radiation temperature, estimated from the energy density or a diluted blackbody parametrization, or to the matter temperature determined by some other method.

3.4.2. Nebular solver

The nebular solver determines the state of the matter assuming that the radiative rates dominates, and is based on the approximations for the populations of ionized and excited states derived by Mazzali & Lucy (1993) and Abbott & Lucy (1985). Following Mazzali & Lucy (1993), the temperature is assumed to be controlled by the radiation field and set to $0.9T_R$, where T_R is the temperature for a diluted blackbody parametrization of the radiation field.

3.4.3. NLTE solver

The NLTE solver determines the state of the matter by solving the statistical and thermal equilibrium equations for the level populations and the temperature, respectively. The solution is determined in two steps. First, thermal equilibrium is scanned for in a configurable temperature interval (based on the solution from a previous Λ -iteration), solving for statistical equilibrium at each step. Based on this estimate, thermal and statistical equilibrium are simultaneously iterated for until convergence is achieved, using a procedure similar to what is described by L03.

Statistical equilibrium The non-linear statistical equilibrium equation system (Eq. 1) is solved by iteration on the level populations. In each step the system is linearised in terms of changes in the level populations, and the rates and their derivatives are calculated using the previous estimate of these. The linearised system is then solved for the level populations using lower-upper (LU) decomposition and back-substitution. If all number derivatives (explicit and implicit) are included this is equivalent to a Newton-Raphson solver, but we leave this as a configurable choice, and in the simplest configuration only the explicit derivatives (i.e. rates per particle) are included.

The equation system may be solved separately for the states of each atom, ignoring any coupling terms, or for all states at once. As the total number of states may be too large for a coupled solution, we provide the possibility to alternate a decoupled solution with a fully coupled solution for the ionization balance. Typically a decoupled solution works well, but charge-transfer reactions and the source-function (used in the on-the-spot approximation) may introduce strong coupling terms. Transition rates for bound-bound and bound-free radiative and collisional processes, as well as for non-thermal, charge-transfer and two-photon processes are all supported, but which ones to include is a configurable choice.

Thermal equilibrium The thermal equilibrium equation (Eq. 2) is solved either using the secant method (initial estimate) or Newtons-Raphson's method (refined estimate), in which case an explicit temperature derivative is used. Heating and cooling rates for bound-bound and bound-free radiative and collisional processes, free-free processes, as well as non-thermal and charge-transfer processes are all supported, but which ones to include is a configurable choice. In addition, an expansion cooling term PdV/dt may also be included, as is motivated in a time-dependent run.

3.4.4. Non-thermal solver

The non-thermal solver determines the non-thermal electron distribution resulting from the radioactive decays, and the fraction of the deposited energy going into heating, excitation and ion-

ization. This is done by solving the Spencer-Fano equation (i.e. the Boltzman equation for electrons) as described in KF92.

3.5. Diffusion solver

The diffusion solver determines the temperature in each cell by solving the thermal energy equation assuming spherical symmetry, homologous expansion, LTE and the diffusion approximation for the radiative flux. This results in a non-linear equation system for the temperature in each cell, which is solved by a Newton-Raphson like technique similar to the one used by Falk & Arnett (1977). Two specific topics require some further discussion though; the Rosseland mean opacity used in the diffusion approximation, and the outer boundary where the diffusion solver is supposed to be coupled to the MC solver.

3.5.1. Opacity

The Rosseland mean opacity used in the diffusion approximation is calculated from the LTE state of the matter and the atomic data. This may sound straightforward, but the bound-bound opacity and in particular, the virtual cell mode (see Sect 3.1.2) complicates things. In the latter case, if the clumps are all optically thin, the opacity may be calculated as a zone average, but otherwise a geometrical aspect enters the problem.

Therefore we calculate the Rosseland mean opacity using an Monte-Carlo method. In each cell a large number of packets are sampled based on the blackbody flux distribution and the zone filling factors. These packets are then followed until they are absorbed, and their path-length averaged to get the Rosseland mean free path. This gives the Rosseland mean opacity, including the bound-bound contribution as well as the geometrical effects arising in a clumpy material

3.5.2. Outer boundary

If the diffusion solver is coupled to an MC solver at the outer boundary, which is the main purpose of it, appropriate boundary conditions must be specified for both the diffusion and the MC solver. As outer boundary condition for the diffusion solver we use the temperature, and as inner boundary condition for the MC solver we use the luminosity. To implement the latter condition we use an approximate method, where packets with total energy $L\Delta t$, sampled from a blackbody distribution at the local temperature are injected at the inner boundary, whereas MC packets propagating inwards are simply reflected at this boundary.

4. Comparisons

In this section we compare JEKYLL to ARTIS (K09) and SUMO (J11), two codes which have similar, but not identical capabilities. ARTIS provides a good test of the MC radiative transfer, which is very similar, but only supports partial NLTE. SUMO on the other hand, provides a good test of the full NLTE problem, but requires steady-state, so no test of the time-dependent radiative transfer is possible. Therefore, the comparisons to ARTIS and SUMO are complementary, and taken together they provide a critical test of the JEKYLL code.

4.1. Comparison with ARTIS

ARTIS is a spectral synthesis code aimed for the photospheric phase presented in K09. Both ARTIS and JEKYLL are based

on the method outlined in L02-L05, but ARTIS only supports a simplified NLTE treatment, where the bound states of the ions are assumed to be populated according to LTE and the energy deposited by the radioactive decays is assumed to be fully thermalized. On the other hand, JEKYLL assumes a spherical symmetric geometry, which is not a limitation in ARTIS. In addition, ARTIS calculates the deposition of the radioactive decay energy by Compton scattering, photo-electric absorption and pair production, whereas JEKYLL use effective grey opacities (based on such calculations). There are also differences in the calculation of photoionization rates, where ARTIS use a simplified treatment, and recombination rates, where ARTIS ignores stimulated emission.

As much as possible, we have synchronized the methods and the atomic data used by JEKYLL and ARTIS. To achieve this we have configured JEKYLL to use a NLTE solution for the ion populations, and otherwise a LTE solution based on the radiation energy temperature (T_j , see K09). Radiative and collisional bound-free rates were included in the ionization equilibrium equation, and (thermal) collisional bound-bound, radiative and (thermal) collisional bound-free and free-free processes, as well as non-thermal heating, were included in the thermal equilibrium equation. The atomic data used by ARTIS is described in K09, and as it is all stored in data-files in a well-defined format, it was quite straight-forward to automatically convert it to the JEKYLL atomic data format. The atomic data should therefore be fully synchronized, whereas the synchronization of the methods should be good enough for a meaningful comparison.

For the comparison we use the Type IIb model 12C from J15, which is also used in the application to Type IIb SNe (Sect. 5). Note that ARTIS do not support non-thermal excitation and ionization, which is crucial for the population of the excited states of He I. Therefore, the setup used for the comparison will not be able to reproduce the He I signature characteristic of Type IIb (and Ib) SNe. However, this is not a problem for the comparison, which will provide a critical test of the MC radiative transfer as well as most of the methods used. The full NLTE capabilities of JEKYLL can not be tested here, and this is instead achieved through the comparison with SUMO in Sect. 4.2.

Figures 1 and 2 shows the bolometric lightcurve and the spectral evolution, respectively, for model 12C as calculated with ARTIS (black) and JEKYLL (red). Clearly, as far as the observational quantities are concerned, the calculations seem to agree well.

4.2. Comparison with SUMO

SUMO is a spectral synthesis code aimed for the nebular phase presented in J11. Similar to JEKYLL, it uses a Λ -iteration scheme, where the radiative transfer is solved with a MC method and the state of the gas determined from statistical and thermal equilibrium. Except for the steady-state assumption, which is required by SUMO and a configurable option in JEKYLL, the main difference between between SUMO and JEKYLL is the MC technique used. Whereas JEKYLL is based on the method by L02-L05, where the constraints of thermal and statistical equilibrium is enforced on the MC radiative transfer, SUMO uses another approach. The initial MC packets for each Λ -iteration are drawn from the total emissivity (excluding electron scattering), and upon bound-free and free-free absorption, the packet is not re-emitted, whereas upon bound-bound absorption the packet is attenuated. This difference in technique should not affect the solution, but could be important for the convergence. It is clear that at high absorption depths, the method used

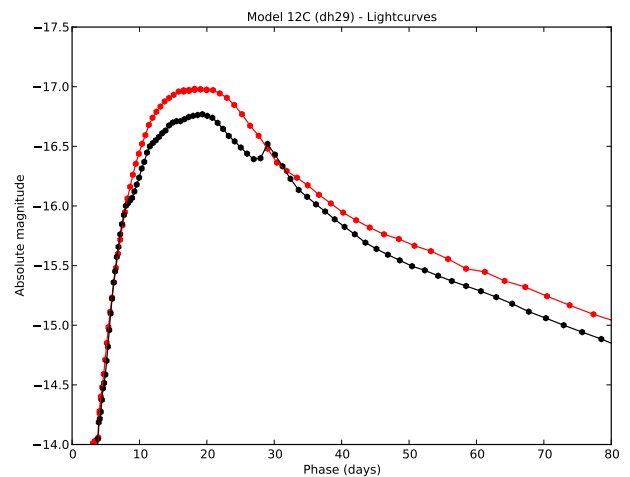


Fig. 1. Comparison of bolometric lightcurve for model 12C as calculated with ARTIS (black) and JEKYLL (red).

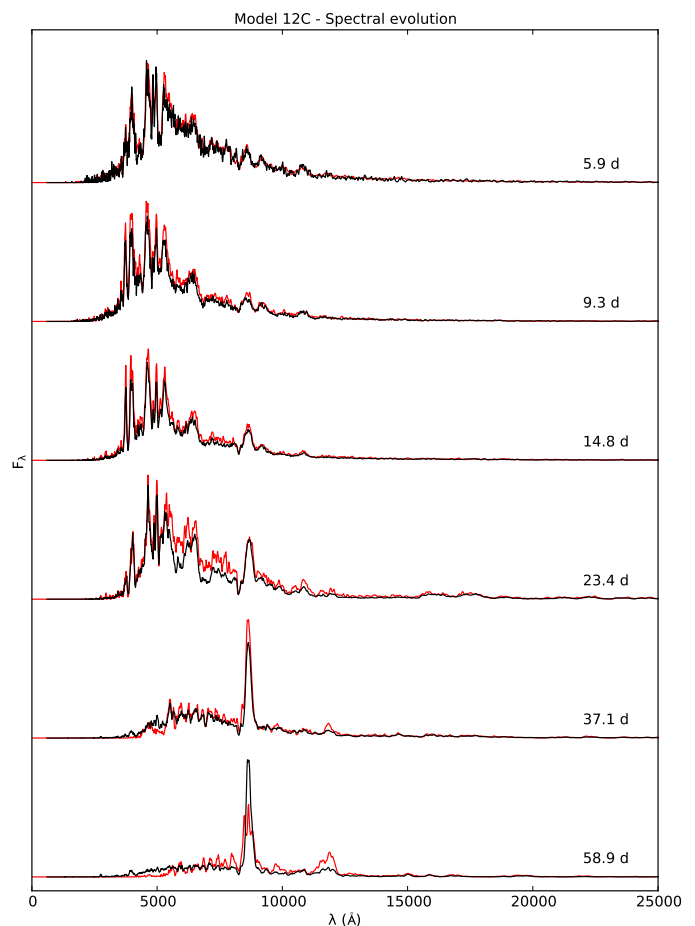


Fig. 2. Comparison of spectral evolution for model 12C as calculated with ARTIS (black) and JEKYLL (red).

by SUMO will suffer from the slow convergence discussed in Sect. 2.1, and is therefore not suited for the photospheric phase. There are also a few differences in the physical assumptions. Whereas JEKYLL correctly sample the frequency dependence of the bound-free emissivity, this is done in a simplified manner for all species but hydrogen by SUMO. On the other hand,

JEKYLL does not take the escape probability from continua and other lines in the Sobolev resonans region into account. However, in general the physical assumptions are similar.

As much as possible, we have synchronized the methods and the atomic data used by JEKYLL with that used for the modelling in J15. To achieve this, JEKYLL was configured to run in steady-state mode, and to use a full NLTE solution including the following: radiative bound-bound, bound-free and free-free processes, thermal collisional bound-bound processes, non-thermal collisional excitation, ionization and heating, as well as charge-transfer and two-photon processes. JEKYLL was also configured to use a recombination correction in a manner similar to SUMO (see J11), and to relax the detailed balance requirement on the radiative bound-free rates. The atomic data used for the modelling in J15 is described in J11 and Jerkstrand et al. (2012). In the case it were stored in data-files in a well-defined format, as for e.g. energy levels and spontaneous emission rates, it were automatically converted to the JEKYLL atomic data format, and otherwise it were added manually to the JEKYLL atomic data files based on the descriptions in J11 and Jerkstrand et al. (2012). Although not complete, the synchronization of the atomic data and the methods should be good enough for a meaningful comparison.

For the comparison we use model 13G from the set of Type IIb models presented in J15, and run steady-state models with JEKYLL at 150, 200, 300, 400 and 500 days. A comparison of the spectral evolution is shown in Fig. 3, and in Figs. 4 and 5 we show comparisons of the evolution of the temperature and the electron fraction, respectively, in each of the different nuclear burning zones. As can be seen, the general agreement of the spectra is quite good, although the match is slightly worse at 500 days. The largest discrepancies are seen in the Mg I 4571 Å line, the O I 11290, 11300 Å line before 300 days, the He I 10830 Å line at 200-300 days, and a number of Fe I features originating from the Fe/Co/He zone at 500 days. That one of the largest discrepancies is seen in the Mg I 4571 Å line is not surprising as magnesium is mainly ionized and the Mg I fraction is small (see J15). This makes the strength of the Mg I 4571 Å line sensitive to this fraction, in turn sensitive to the network of charge transfer reactions. The evolution of the temperature shows a good agreement, except for the He/N and H zones at early times, whereas the evolution of the electron density shows a slightly worse agreement. In general, the agreement in the temperature and electron fraction is worse at early times than later on, which is not surprising as some approximations made by SUMO are better suited for later phases. Given that the data and methods are not entirely synchronized the general agreement appears to be good and confirms that JEKYLL is working properly.

5. Application to Type IIb SNe

In J15 a set of Type IIb models differing in initial mass, mixing and a number of other parameters were introduced and evolved through the nebular phase. Among those, model 12C¹, which has an initial mass of 12 M_⊙, and strong mixing, was found to give the best match to the observed nebular spectra (J15) and lightcurves (E15) of SN 2011dh. It is therefore of great interest to explore how well this model reproduces the early spectra and lightcurves, something which is now possible using JEKYLL. The early bolometric lightcurve was modelled in E15 using the

¹ Model 12F, preferred in E15, differs from model 12C only in the optical depth of the dust.

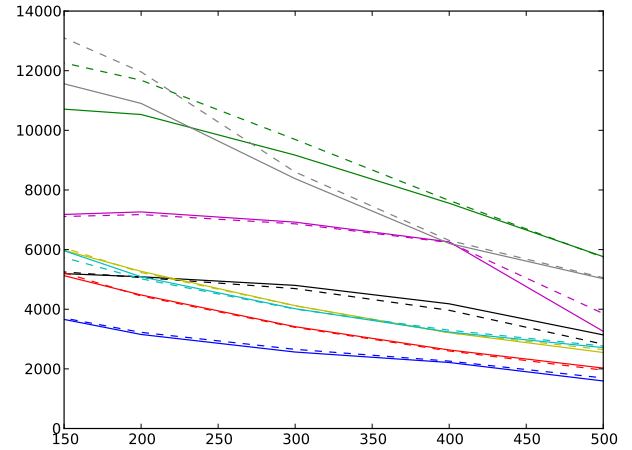


Fig. 4. Comparison of the evolution for the temperature for model 13G in the Fe/Co/He (black) Si/S (blue), O/Si/S (red), O/Ne/Mg (yellow), O/C (cyan), He/C (magenta), He/N (green) and H (grey) zones, as calculated with SUMO (dashed lines) and JEKYLL (solid lines).

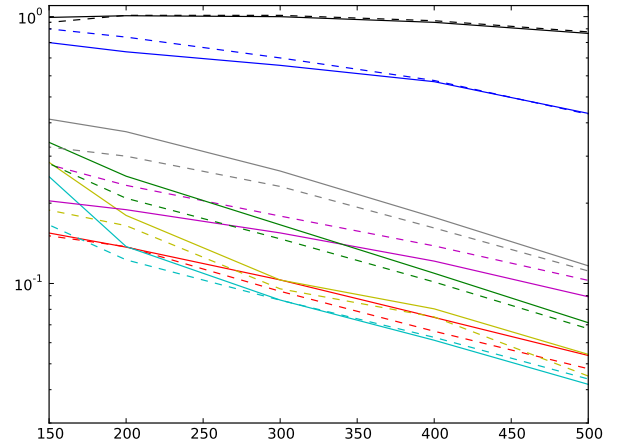


Fig. 5. Comparison of evolution of the electron fraction for model 13G in the Fe/Co/He (black) Si/S (blue), O/Si/S (red), O/Ne/Mg (yellow), O/C (cyan), He/C (magenta), He/N (green) and H (grey) zones as calculated with SUMO (black) and JEKYLL (red).

hydrodynamical, LTE-based code HYDE², and we can now investigate how well this simplified approach compares with a full NLTE calculation. It is also worth comparing to the NLTE models of stripped envelope (SE; Type IIb, Ib and Ic) SNe presented by Dessart et al. (2015, 2016). Those models where evolved with CMFGEN and in particular the Type IIb model 3p65Ax1 shares many properties with model 12C.

In Sect. 5.1 we describe the basic properties of the model and in Sects. 5.2, 5.3, 5.4 and 5.5 we discuss its spectral, photometric, colour and bolometric evolution and compare to observations of SN 2011dh. We also discuss the physical processes giving rise to the observed evolution and in Figs. 6 and ?? we show the evolution of the basic matter and radiation quantities in model 12C. The former shows the evolution of the temperature, electron fraction, radioactive energy deposition as well as

² Set up to run in homologous mode

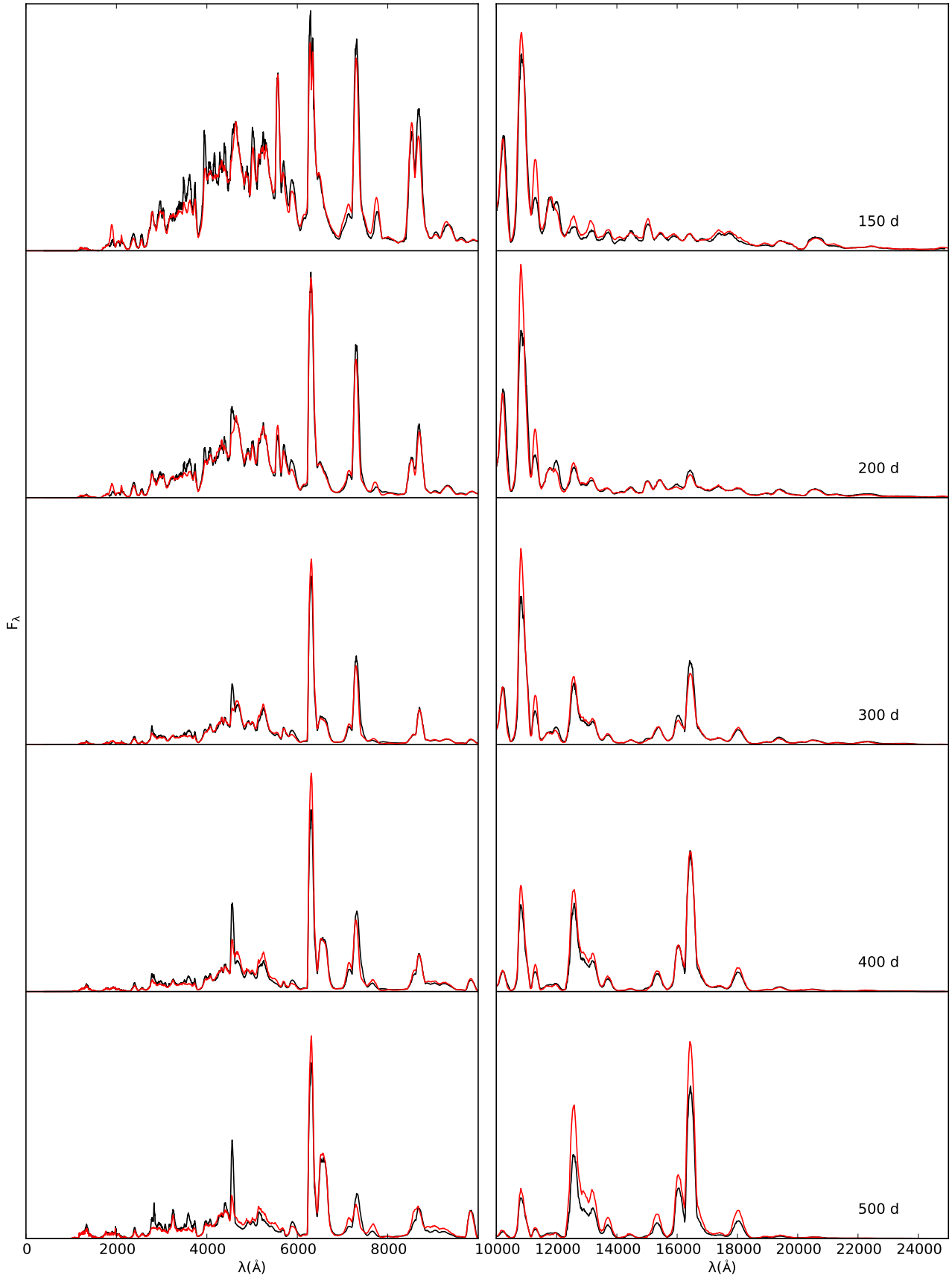


Fig. 3. Comparison of spectra for model 13G at 150, 200, 300, 400 and 500 days as calculated with SUMO (black) and JEKYLL (red).

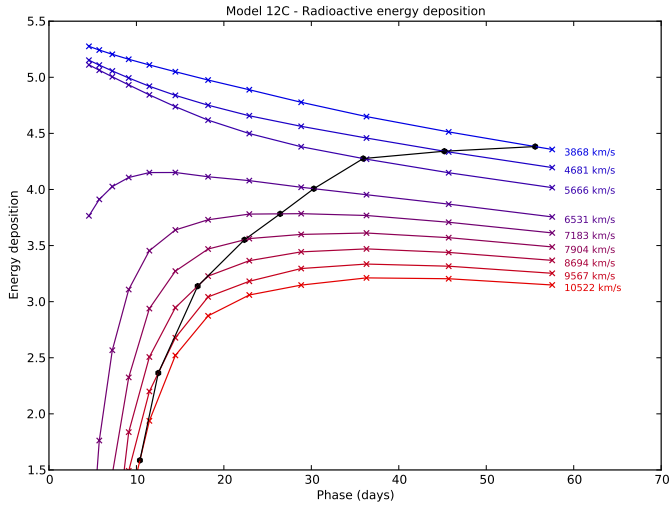


Fig. 7. Evolution of the radioactive energy deposition in the helium envelope for model 12C.

the photospheric radius, whereas the latter shows the evolution of the J, H and K moments of the radiation field, as well as the Eddington factor. Finally, in Sects. 5.6 and 5.7 we discuss the effects of NLTE and macroscopic mixing on the calculated spectra and lightcurves.

5.1. Model description

A full description of model 12 C was given in J15, but we repeat the basic properties here. The masses and abundances for the carbon-oxygen core and the helium envelope are adopted from a stellar evolutionary model by Woosley & Heger (2007) with an initial mass of $12 M_{\odot}$, including also the yields from the explosive nucleosynthesis. The carbon-oxygen core is assumed to have a constant density, and the helium envelope to have the same density profile as model He4R270 by Bersten et al. (2012). In addition, a $0.1 M_{\odot}$ hydrogen envelope based on models by Woosley et al. (1994) was attached. The velocities of the interfaces between the carbon-oxygen core, the helium envelope and the hydrogen envelope were set to 3500 and 11000 km/s, respectively based on observations of SN 2011dh.

Based on the original onion-like nuclear burning structure, five compositional zones (O/C, O/Ne/Mg, O/Si/S, Si/S and Fe/Co/He) were identified in the carbon-oxygen core, and two compositional zones (He/N and He/C) were identified in the helium envelope. To mimic the mixing of the nuclear burning zones in the explosion due to hydrodynamical instabilities, two scenarios with different degrees of mixing (medium and strong) were explored in J15. Of those, the strong mixing scenario used for model 12 C corresponds to a fully mixed carbon-oxygen core and about half of the radioactive Fe/Co/He material mixed into the inner part of the helium envelope. As in J15 we take the macroscopic nature of the mixing into account using the virtual cell method (Sect. 3.1.2), but we have also run a model with microscopic mixing by just averaging the abundances in the different compositional zones. This method is used for the CMFGEN models by Dessart et al. (2015, 2016) as well as in many other works and therefore a comparison is highly motivated.

As for the HYDE models in E15, the model was evolved from 1 day with the initial temperature profile taken from the best-fit hydrodynamical model for SN 2011dh from that paper. This SN model was based on a bare helium core model, and

therefore the cooling of the thermal explosion energy, lasting for a few days in a model with a hydrogen envelope, is ignored. As mentioned in E15, the subsequent evolution is powered by the continuous injection of radioactive decay energy, and the choice of initial temperature profile is not critical, although it may have some effect on the early evolution.

In the runs we have used the diffusion solver in the inner region coupled to the MC/NLTE solvers at a continuum optical depth of 50. (+More?)

The atomic data used is the same as for the comparison with SUMO (Sect. 4.2), but with the following modifications. The highest ionization stage were increased to VI for all species, and the stage III ions were updated to include at least 50 levels for elements lighter than Sc, and at least 200 levels for heavier elements, using online data provided by NIST³ and R. Kurucz⁴. Total recombination rates for the stage III ions were adopted from the online table provided by S. Nahar⁵ whenever available, and otherwise from Shull & van Steenberg (1982). For ionization stages IV to VI we only included the ground-state multiplets, adopted the photo-ionization cross-section by Verner & Yakovlev (1995) and Verner et al. (1996) and assumed the populations to be in LTE with respect to stage IV.

5.2. Spectral evolution

Figures 8 and 9 show the spectral evolution for model 12C between 0 and 150 days, where the former displays the process, and the latter the location giving rise to the emission. Furthermore, in Fig. 10 we compare the spectral evolution in the optical and NIR to observations of SN 2011dh. As seen in Fig. 10, there is a good qualitative, and in many aspects also quantitative agreement, between model 12C and the observations of SN 2011dh. Before ~ 10 days, when the emission comes mainly from the hydrogen envelope the agreement is a bit worse (not shown). This is possibly an effect of the choice of initial conditions for the model (see Sect. 5.1), where the initial cooling of the explosion energy, lasting a few days, has been ignored.

The main signature of a Type IIb SNe is the transition from a hydrogen to a helium dominated spectrum, and this is well reproduced by the model. Initially, $H\alpha$ in the optical and the Paschen-series in the near-infrared (NIR) are strong in the model and emission from the hydrogen envelope is dominating. Already at ~ 10 days emission from the helium envelope starts to dominate redwards $\sim 5000 \text{ \AA}$, and between 10 and 15 days the helium lines appear, grow stronger, and eventually dominate the spectrum at ~ 40 days. In the model, $H\alpha$ and Paschen-line emission disappears on a similar time-scale, completing the transition, although $H\alpha$ remains considerably longer in absorption. The first 40 days is also the period over which the contribution from continuum processes fades away. Initially, this contribution is substantial redwards $\sim 5000 \text{ \AA}$ and dominating in the NIR, but then quickly fades away although it remains important in the H -band and redwards 23000 \AA until ~ 40 days.

After ~ 40 days, emission from the carbon-oxygen core becomes increasingly important and at ~ 100 days it dominates redwards $\sim 5000 \text{ \AA}$. As a consequence, emission from heavier elements abundant in the core increase, in particular after ~ 100 days when the strong forbidden lines from oxygen and Calcium appear. This is also the moment when the carbon-oxygen core becomes fully transparent, at least in the continuum (see Fig.6),

³ www.nist.gov

⁴ <http://www.cfa.harvard.edu/amp/ampdata/kurucz23/sekur.html>

⁵ http://www.astronomy.ohio-state.edu/~nahar/_nahar_radiative_atomic_data/

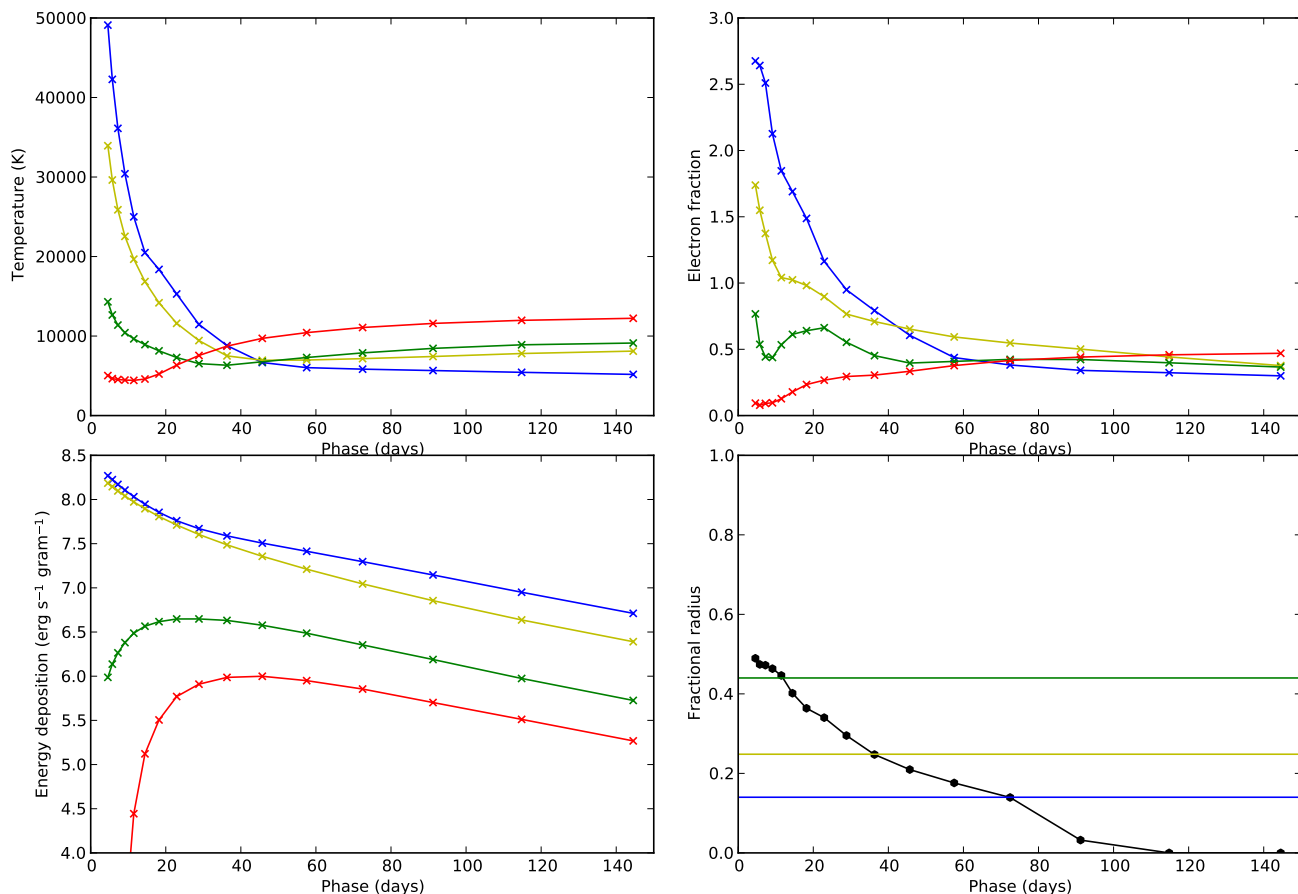


Fig. 6. Evolution of the temperature (upper left panel), electron fraction (upper right panel) and radioactive energy deposition (lower left panel) in the oxygen core (blue), inner/outer (green/yellow) helium envelope and the hydrogen envelope (red) for model 12C. In the lower right panel we show the evolution of the (Rosseland mean) continuum photosphere as well as the outer borders of the carbon-oxygen core and inner/outer (green/yellow) helium envelope.

and therefore marks the transition into the nebular phase. This transition, itself a demanding test of the code, is quite nicely reproduced by the model. As discussed in Sect. 5.7, this is partly thanks to our treatment of the macroscopic mixing.

Below, we discuss the most important lines originating from the different species in some detail (Sect. 5.2.1-5.2.5) as well as the line velocities measured from their absorption minimum (Sect. 5.2.6), and again compare to observations of SN 2011dh.

5.2.1. Hydrogen

The contribution from hydrogen lines to the model spectrum is shown in Fig. 8, and as mentioned it is initially strong, but quickly fades away after ~ 10 days, when the photosphere retreats into the increasingly transparent helium envelope (see Figs. 6 and 9). At this moment most of the hydrogen in the envelope have recombined, and the recombination driven Paschen lines, which are initially strong, quickly disappear (although Paschen α is still present at ~ 25 days). The Balmer line emission disappears on a similar time-scale, whereas the absorption remains for a longer time as the $n = 2$ level is also populated by other means. Contrary to the other Balmer lines, $H\alpha$ initially shows a clear P-Cygni profile, but after ~ 10 days it becomes increasingly blended with the He I 6678 Å line and attains the double-peaked shape so characteristic in Type IIb SNe.

Figure 11 shows the evolution of the Balmer lines as compared SN 2011dh. The evolution is qualitatively similar, but the absorption is significantly stronger and remains longer in the model, suggesting the $\sim 0.05 M_{\odot}$ of hydrogen in the model to be larger than for SN 2011dh. This is in line with the 0.02-0.04 and $0.024 M_{\odot}$ of hydrogen estimated through spectral modelling of SN 2011dh by E14⁶ and Marion et al. (2013), respectively. In agreement with the spectral modelling in E14, we also find that the absorption minimum of the Balmer lines asymptotically approaches the velocity of the hydrogen/helium envelope interface (see also Fig. 17). The Type IIb models by Dessart et al. (2015, 2016) (e.g. model 3p65Ax1) behave in a similar way, and a saturation of the absorption velocity for the Balmer lines is observed in most Type IIb SNe (see e.g. Liu et al. 2016). The saturation velocity varies among different SNe, and for the most well-observed Type IIb SNe 1993J, 2011dh and 2008ax it is ~ 9000 , ~ 11000 and ~ 13000 km/s (E14), respectively, consistent with the progressively lower hydrogen masses inferred for these SNe by other means.

⁶ Using an early version of JEKYLL assuming steady-state, LTE and scattering only.

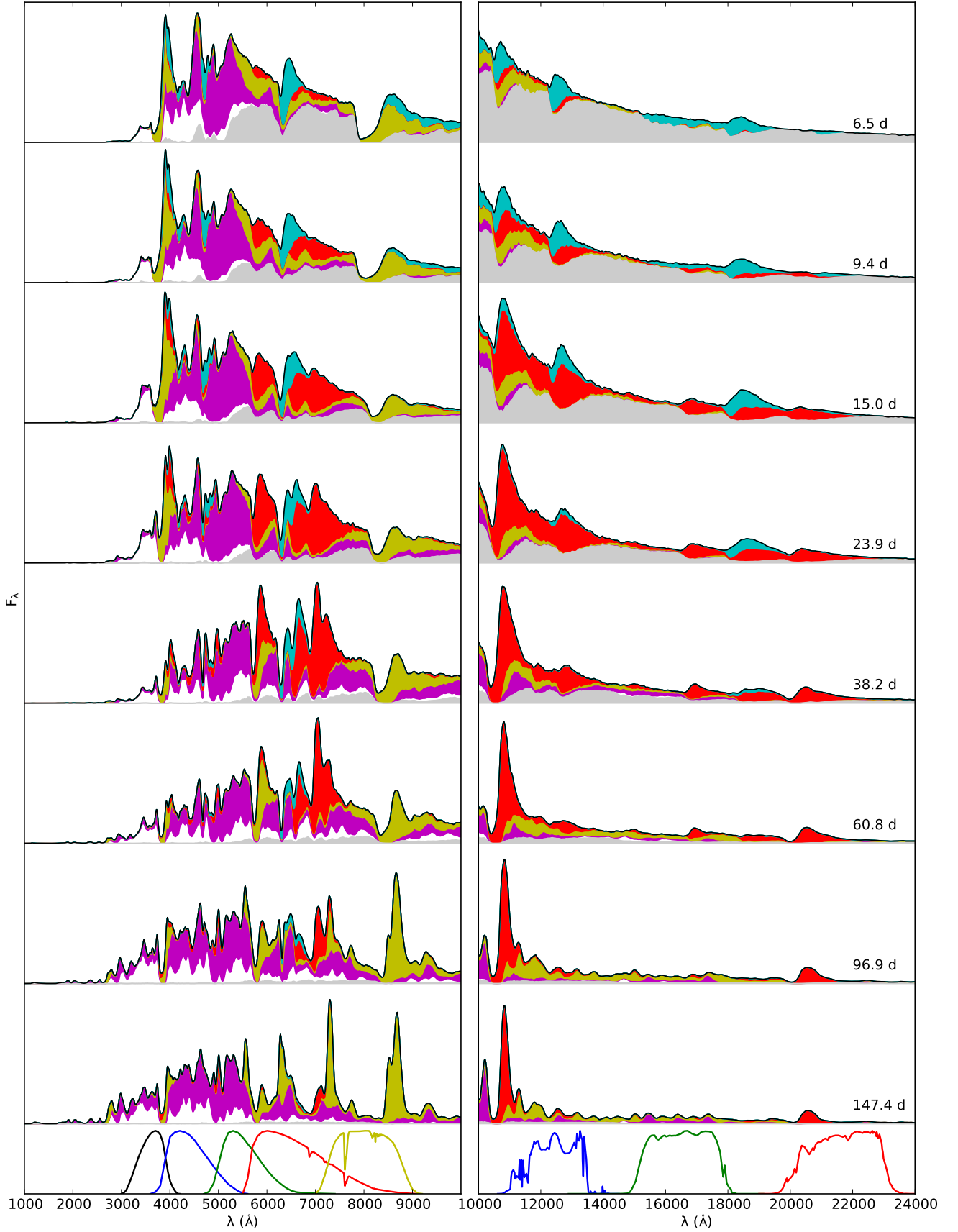


Fig. 8. Spectral evolution in the optical (left panel) and NIR (right panel) for model 12C as calculated with JEKYLL. In the spectra we show the contributions to the emission from bound-bound transitions of hydrogen (cyan), helium (red), carbon-calcium (yellow), scandium-manganese (white) and iron-nickel (magenta) as well as continuum processes (grey). At the bottom we show the transmission profiles of the optical Johnson-Cousine U (black), B (blue), V (green), R (red) and I (yellow) bands and the NIR 2MASS J (blue), H (green) and K (red) bands.

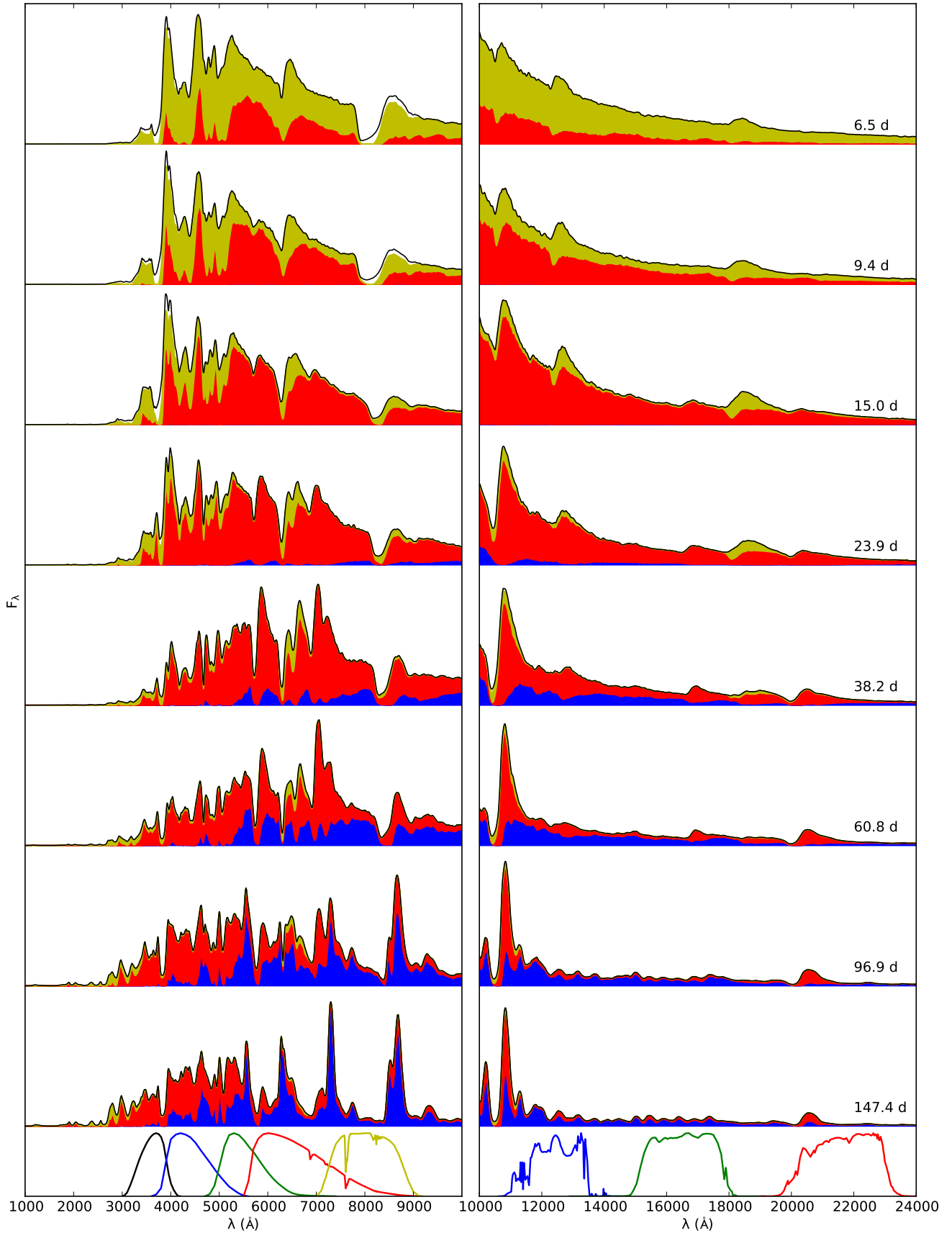


Fig. 9. Spectral evolution in the optical (left panel) and NIR (right panel) for model 12C as calculated with JEKYLL. In the spectra we show the contributions to the emission from the carbon-oxygen core (blue), and the helium (red) and hydrogen (yellow) envelopes. At the bottom we show the transmission profiles of the optical Johnson-Cousine U (black), B (blue), V (green), R (red) and I (yellow) bands and the NIR 2MASS J (blue), H (green) and K (red) bands.

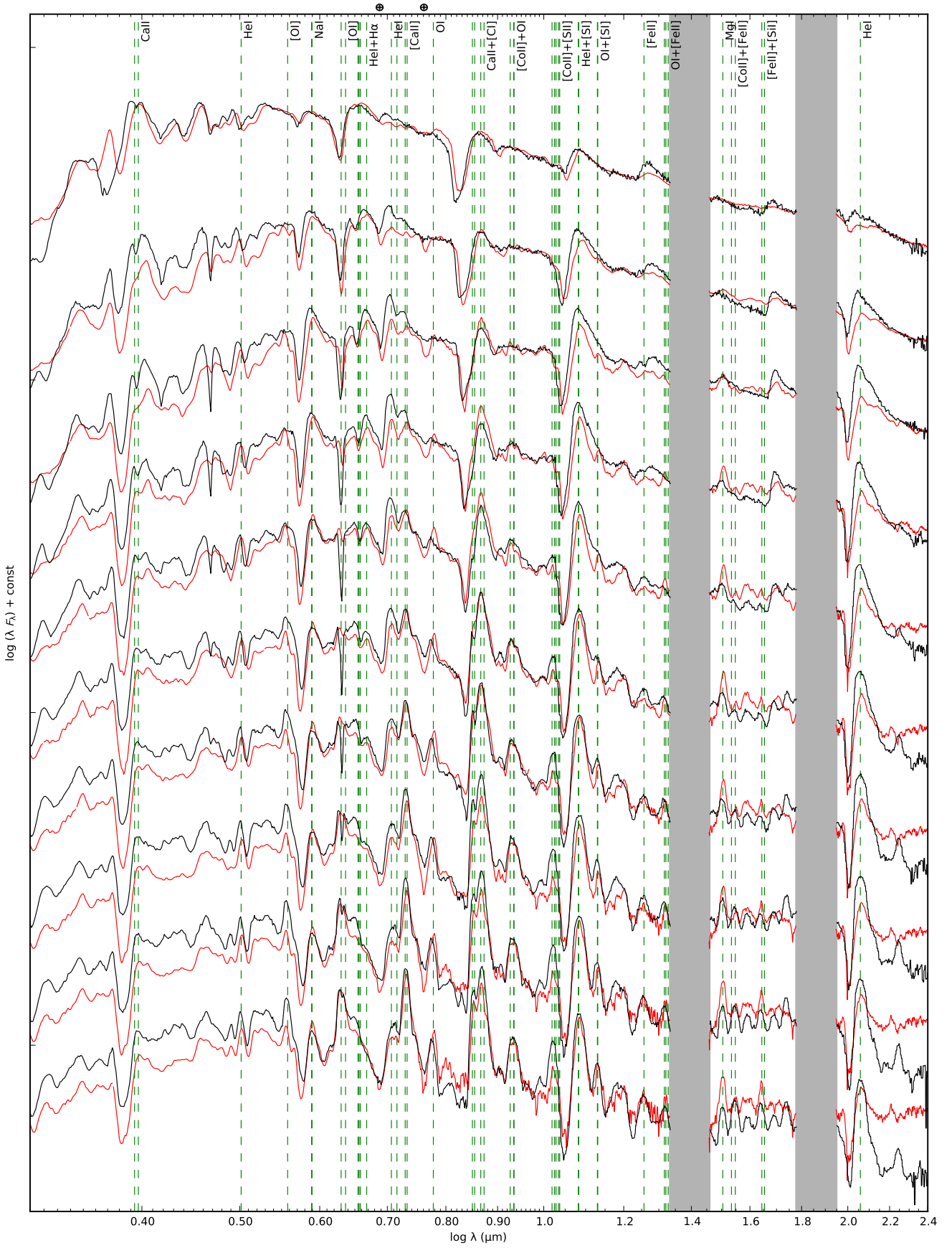


Fig. 10. Spectral evolution for model 12C as calculated with JEKYLL (black) compared to the observations of SN 2011dh (red). Spectra from 10 equally spaced epochs between 15 and 150 days are shown, where those of SN 2011dh have been interpolated as described in E14.

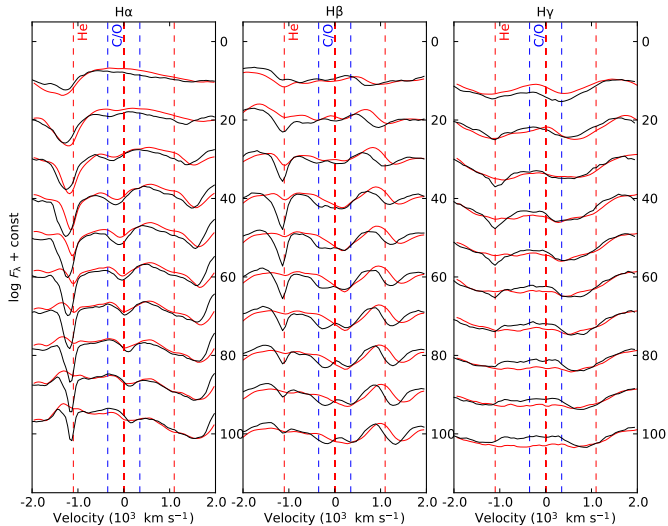


Fig. 11. Evolution of hydrogen lines for model 12C as calculated with JEKYL (black) compared to the observations of SN 2011dh (red). Spectra from 10 equally spaced epochs between 10 and 100 days are shown, where those of SN 2011dh have been interpolated as described in E14. Here, as well as in Figs. 12-16, we also show the velocity extent of the He envelope (red lines) and the C/O core (blue lines).

5.2.2. Helium

The contribution from helium lines to the model spectrum is shown in Fig. 8, and as mentioned it increases strongly between 10 and 15 days, dominates the spectrum between 20 and 60 days and thereafter fades away in the optical but remains important in the NIR. Figures 12 and 13 shows the evolution of the optical (He I 5876 Å, 6678 Å and 7065 Å) and NIR (He I 10830 Å, 17007 Å and 20581 Å) lines as compared to SN 2011dh. The He I 6678 Å and 20581 Å lines belong to the singlet branch and the others to the triplet branch of He I ion, ending at the meta-stable $2s^1S$ and $2s^3S$ levels, respectively, which are directly linked to the ground state. The He I 5876 Å, 6678 Å and 10830 Å lines are quite well reproduced by the model, whereas the He I 7065 Å and 20581 Å lines seem to be a bit overproduced, and the weaker He I 17007 Å line (mainly seen in emission) is considerably stronger than in the observed spectra. We note, that the He I 20581 Å line is particularly sensitive to non-thermal excitation (Jerkstrand et al. 2015; Dessart et al. 2012), so the overproduction of this line could indicate that the mixing of the radioactive Fe/Co/He material is too strong. Note also, that after ~ 50 days, most of the He I 5876 Å line emission begin to scatter into the Na I 5890,5896 Å line.

As seen in Fig. 13 (and Fig. 17), the absorption-minimum of the He I 10830 Å line appears near the photosphere and moves outward in velocity until ~ 40 days, a behaviour repeated to some degree in the He I 20581 Å line. As discussed in E14, this behaviour is also observed, although for SN 2011dh the optical helium lines showed a similar, but less pronounced trend. In E14 we suggested that the appearance and subsequent evolution of the helium lines was driven mainly by the ejecta becoming optically thin to the γ -rays. This idea is supported by Fig. 7, which shows the evolution of the radioactive energy deposition in the helium envelope. Between 10 and 15 days we see a strong increase in the energy deposition outside the photosphere, corresponding well to the appearance and increasing strength of the helium lines. We also see that the energy deposition in the outer-

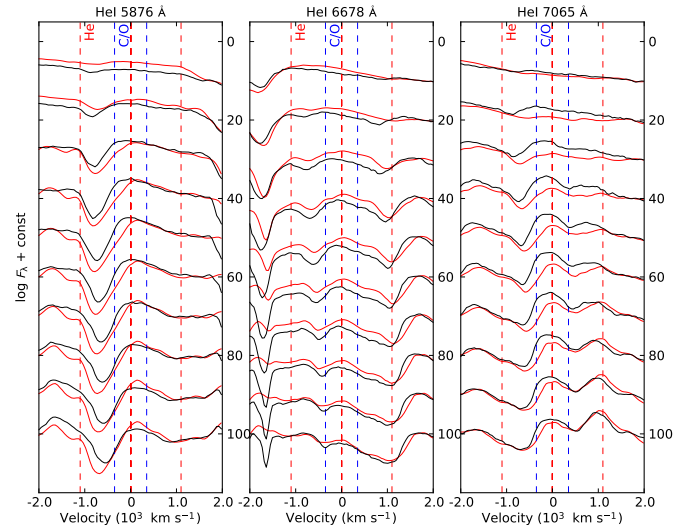


Fig. 12. Evolution of optical helium lines for model 12C as calculated with JEKYL (black) compared to the observations of SN 2011dh (red). Spectra from 10 equally spaced epochs between 10 and 100 days are shown, where those of SN 2011dh have been interpolated as described in E14.

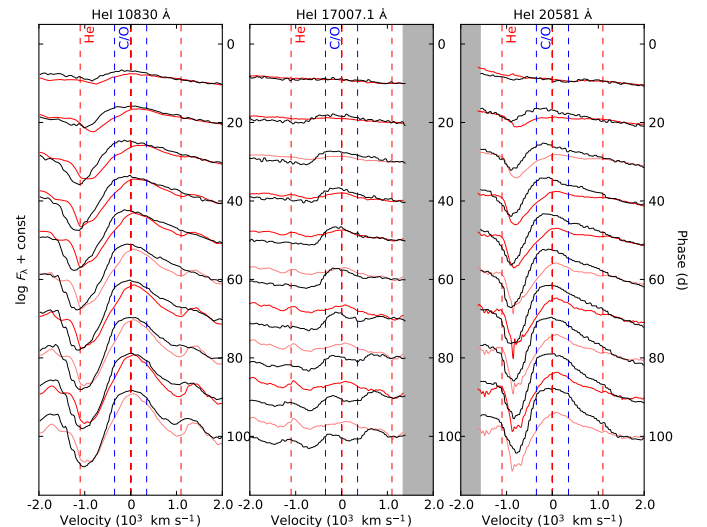


Fig. 13. Evolution of NIR helium lines for model 12C as calculated with JEKYL (black) compared to the observations of SN 2011dh (red). Otherwise as in Fig. 12.

most helium layers continues to increase to ~ 40 days, which may explain the evolution of the He I 10830 Å line. The outward migration of the absorption of the He I 10830 Å line is also present in the Type I/IIb models (e.g. model 3p65Ax1) by Dessart et al. (2015, 2016), and was noted and discussed by the authors, who also provide a similar explanation.

5.2.3. Carbon-calcium

The contribution from carbon-calcium lines to the model is shown in Fig. 8, and except for the calcium lines which are strong at all times, the contribution increases after ~ 40 days when the core, rich in these elements becomes increasingly transparent (see Fig. 9). Figure 14 shows the evolution of the Ca II 3934,3968 Å, 8498,8542,8662 Å and [Ca II] 7291,7323

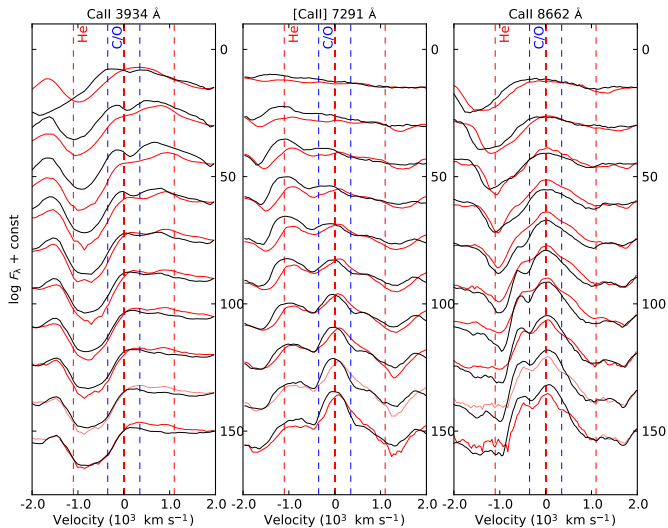


Fig. 14. Evolution of calcium lines for model 12C as calculated with JEKYL (black) compared to the observations of SN 2011dh (red). Spectra from 10 equally spaced epochs between 15 and 150 days are shown, where those of SN 2011dh have been interpolated as described in E14.

Å lines as compared to SN 2011dh. In the model, the two former mainly forms in the helium envelope whereas the latter forms in the core. Except before ~ 15 days the evolution of the Calcium lines is well reproduced by the model. However, before ~ 15 and ~ 10 days, respectively, the absorption in the Ca II 3934, 3968 Å and Ca II 8498, 8542, 8662 3934 Å lines extend throughout the hydrogen envelope in the model. As mentioned before, this is possibly an effect of the choice of initial conditions for the model.

Figure 15 shows the evolution of the O I 5577 Å, 6300, 6364 Å, 7774 Å and 11290, 11300 Å and Mg I 15040 Å lines as compared to SN 2011dh. In the model, these lines forms mainly in the core, although the O I 7774 Å line also have a contribution from the helium envelope, at least to begin with. The evolution of the oxygen lines is fairly well reproduced, but the O I 7774 and 11290, 11300 Å lines appear later and are initially weaker than observed for SN 2011dh. The O I 9263 Å line is also present in the model but is blended with the [Co II] 9338, 9344 Å line (see below). In the model, the early (near peak) feature at ~ 9200 Å is mainly caused by the Mg II 9218-9244 Å line, and later the Mg I 15040 Å line appears. The latter is reasonably well reproduced, but appears later and is initially weaker than observed for SN 2011dh. We note that about half of the radioactive Fe/Co/He material was mixed into the helium envelope, whereas the oxygen and Magnesium rich material in the core was not, which may explain the early suppression of several oxygen and magnesium lines as compared to observations. In the model, the feature emerging at ~ 11800 Å after ~ 60 days is mainly caused by the C I 11760 Å line, and towards ~ 150 days the [C I] 8727 Å line begins to contribute significantly to the blend with the Ca II 8498, 8542, 8662 Å line.

5.2.4. Scandium-manganese

The contribution from scandium-manganese lines to the model spectrum is shown in Fig. 8, and is dominating in the 3000-4000 Å region and strong in the 4000-5000 Å region at all times. After ~ 40 days it also contributes significantly to the optical emis-

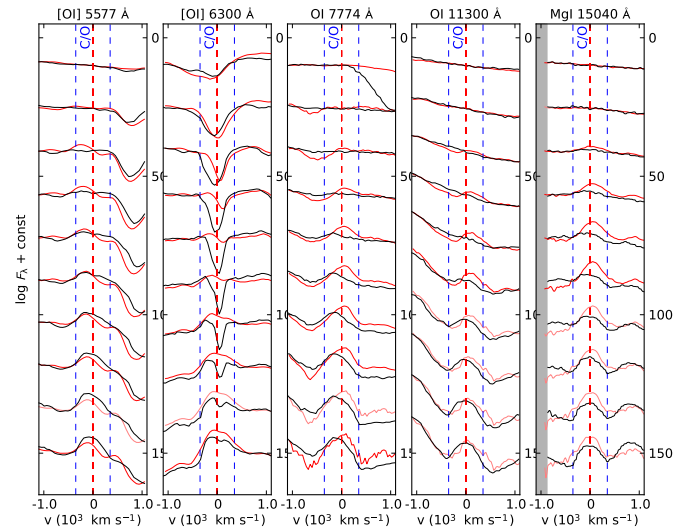


Fig. 15. Evolution of oxygen and magnesium lines for model 12C as calculated with JEKYL (black) compared to the observations of SN 2011dh (red). Otherwise as in Fig. 14.

sion redwards 5000 Å. The emission is the result of scattering and fluorescence in a large number of transitions and individual lines are hard to distinguish. Nevertheless, blocking caused by scandium-manganese lines is important for the suppression of the total emission bluewards ~ 5000 Å, and in particular in the 3000-4000 Å region, corresponding roughly to the *U*-band (see Fig. 8).

5.2.5. Iron-nickel

The contribution from iron-nickel lines to the model spectrum is shown in Fig. 8, and this contribution is strong at all times, in particular in the 4000-5500 Å range. After ~ 40 days the contribution from iron-nickel increases also at other wavelengths, likely due to emission from the increasingly transparent core (see Fig. 9), where about half of the Fe/Co/He material resides. Except for the *U*-band (see Sect. 5.2.4), blocking through scattering and fluorescence in numerous iron lines is the main cause for the suppression of the emission bluewards ~ 5500 Å, so important in shaping the spectra of SE SNe. However, with a few exceptions, like the Fe II 5169 Å line, individual iron lines are typically strongly blended and hard to distinguish. The contribution from nickel is insignificant at all times, but after ~ 50 days cobalt begins to contribute to the spectrum with several distinct lines.

Figure 16 shows the evolution of the Fe II 5169 Å and [Co II] 9338, 9344 Å, 10190, 10248, 10283 Å and 15475 Å lines as compared to SN 2011dh. The Fe II 5169 Å line is reasonably well reproduced, but initially absorption occurs at higher velocities than observed, a discrepancy that disappears towards 150 days. As mentioned the [Co II] 9338, 9344 Å line is blended with the O I 9338, 9344 Å line, and this blend seems to be well reproduced by the model. The other [Co II] lines at 10190, 10248, 10283 Å and 15475 Å seem to be a bit overproduced by the model. The iron and cobalt lines are interesting as they are directly linked to the distribution of the Fe/Co/He material in the ejecta, and the discrepancies seen may indicate that the mixing of this material is different than in the model. The absorption minimum of the Fe II 5169 Å line has been suggested a good tracer of the photosphere

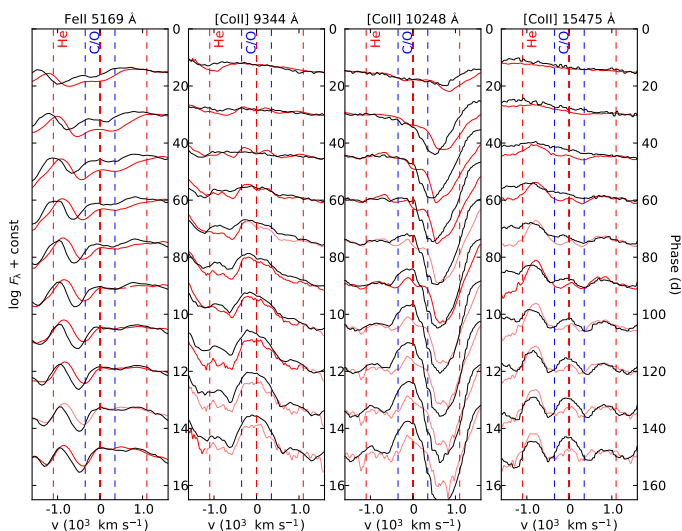


Fig. 16. Evolution of iron and cobalt lines for model 12C as calculated with JEKYLL (black) compared to the observations of SN 2011dh (red). Otherwise as in Fig. 14.

by several authors, and in Sect. 5.2.6 we discuss this issue as well as the distribution of the Fe/Co/He material further.

5.2.6. Line velocities

Figure 17 shows the velocity evolution of the absorption minima of the $H\alpha$, $H\beta$, He I 5876 Å, He I 6678 Å, He I 10830 Å, He I 20581 Å, and Fe II 5169 Å lines, as well as the (Rosseland mean) continuum photosphere (compare; E15: Fig. 14). Towards 100 days, the $H\alpha$ velocity approaches the velocity of the interface between the helium and hydrogen envelopes (11000 km s^{-1}), whereas the $H\beta$ velocity quickly levels out near this value. Note that the high $H\alpha$ velocities observed before ~ 10 days for SN 2011dh are not reproduced by the model, which could again be related to our choice of initial conditions. As mentioned, in agreement with observations, the He I 10830 Å line appears near the photosphere and moves outward in velocity until ~ 40 days. Another interesting agreement is that the velocity saturates at a value very close to that of $H\alpha$, which in the model is explained by a high optical depth for this line all the way out to the hydrogen envelope. In reasonable agreement with observations, the evolution of the He I 20581 Å velocity is almost flat at $\sim 8000 \text{ km/s}$, increasing slightly towards ~ 40 days. The He I 5876 Å and 6678 Å velocities differ more, and the slight increase observed for the He I 5876 Å velocity towards ~ 40 days is not reproduced by the model.

The evolution of the Fe II 5169 Å velocity follows that of the (Rosseland mean) continuum photosphere until ~ 30 days, confirming the claim that this line is a good tracer of the photosphere during the diffusion phase. However, as mentioned before, this velocity is higher than observed for SN 2011dh, although the discrepancy disappears towards 150 days (see Fig. 16). It is worth noting that the Fe II 5169 Å velocity reach a plateau near $\sim 6000 \text{ km/s}$, a value close to the maximum velocity for the Fe/Co/He material. This is an hint that the amount of such material mixed out in the helium envelope could be too large, which in turn may force the photosphere to too high velocities for too long time.

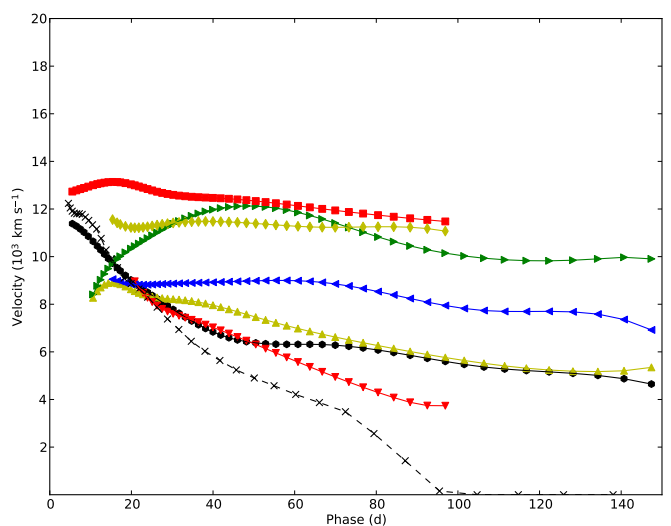


Fig. 17. Velocity evolution of the absorption minimum of the $H\alpha$ (red squares), $H\beta$ (yellow diamonds), He I 5876 Å (yellow upward triangles), He I 6678 Å (red downward triangles), He I 10830 Å (green rightward triangles), He I 20581 Å (blue leftward triangles) Å, and Fe II 5169 Å (black circles) lines for the model 12C as calculated with JEKYLL. The black crosses show the velocity evolution of the (Rosseland mean) continuum photosphere ($\tau = 2/3$).

5.3. Photometric evolution

Figure 18 shows the broad-band lightcurves for model 12C between 0 and 150 days as compared to observations of SN 2011dh. In agreement with observations, the maximum occurs at increasingly later times for redder bands and the drop onto the tail is more pronounced (deeper and faster) for bluer bands. Also in agreement with observations, the early (before 100 days) tail decline rates are generally higher for redder bands, with the J -band lightcurve having the steepest slope and the U -band lightcurve being almost flat. As have been noted in several sample studies (i.e. Taddia et al. 2015, 2017), the former two of the lightcurve properties discussed here are shared not only by SN 2011dh, but by stripped envelope (SE; Type IIb, Ib and Ic) SNe in general. They are also in agreement with the SE-SNe NLTE models presented by Dessart et al. (2015, 2016), and the lightcurves of the Type IIb model 3p65Ax1 are particularly similar to those of model 12 C.

Although the overall agreement with observations is quite good, there are several differences between the model and the observations of SN 2011dh worth noting. Most notable are the differences in the U , J and K -bands and the evolution between 25 and 50 days, which is slower in R and bluer bands than observed for SN 2011dh. The growing discrepancy in the K -band could be related to dust formation in the ejecta (E15), and might suggest that this happens earlier than proposed in E15. Some of the discrepancy in the U -band could be explained by an underestimate of the extinction, but not all as the discrepancy is considerably larger on the tail than at peak.

5.4. Colour evolution

Figure 19 shows the $U - V$, $B - V$, $V - I$ and $V - K$ colour evolution for model 12C between 0 and 100 days as compared to observations of SN 2011dh. Initially, we see a bluerward trend in all colours reaching a minimum at ~ 10 days. Subsequently

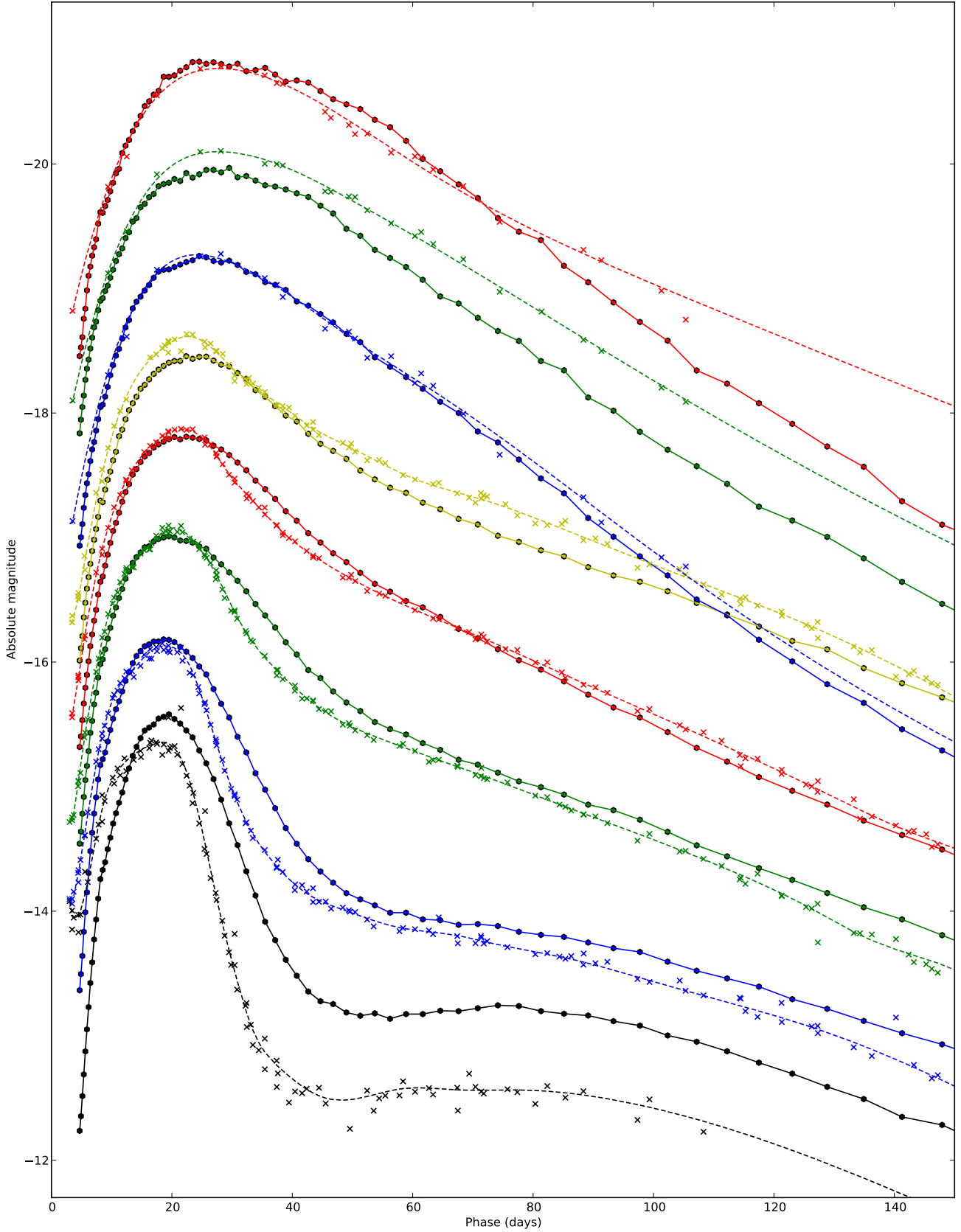


Fig. 18. Broadband optical and NIR lightcurves for model 12C as calculated with JEKYLL (solid lines and circles) compared to observations of SN 2011dh (dashed lines and crosses). From bottom to top we show the U (black), B (blue), V (green), R (red), I (yellow), J (blue), H (green) and K (red) band lightcurves, which for clarity have been shifted with 0.8, 0.3, 0.0, -0.5, -1.2, -1.7, -2.5 and -3.0 mags, respectively.

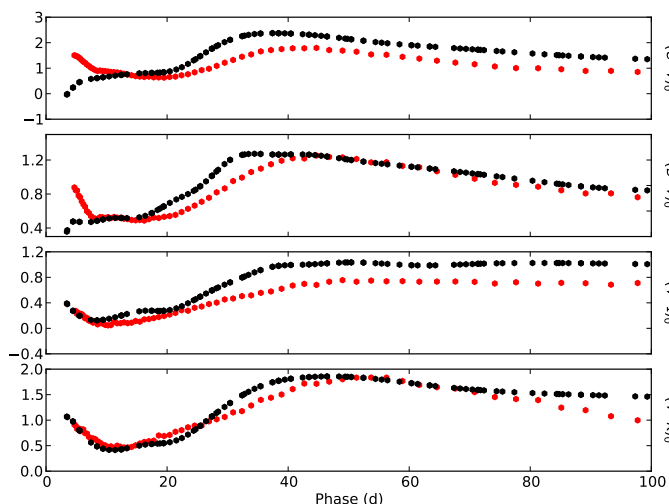


Fig. 19. $U - V$, $B - V$, $V - I$ and $V - K$ colour evolution for model 12C as calculated with JEKYLL (black) compared to observations of SN 2011dh (red).

all colours redden and reaches a maximum at ~ 40 days, in turn followed by a slow blueward trend for all colours, although the $V - I$ colour stays almost constant. This behaviour is in agreement with observations, although there we do not observe an initial blueward trend in the $U - V$, $B - V$ colours, likely due to the influence of an initial cooling tail, not present in the model due to our choice of initial conditions. As have been noted in several sample studies (i.e. Stritzinger et al. 2017), the properties of the colour evolution discussed here are shared not only by SN 2011dh, but by SE-SNe in general. They are also in agreement with the SE-SNe NLTE models presented by Dessart et al. (2015, 2016), and the colour evolution of the Type IIb model 3p65Ax1 is particularly similar to that of model 12 C. As was noted for the lightcurve, the model evolution after ~ 20 days is a bit slower than observed for SN 2011dh. The model $V - I$ and $U - V$ colours are bluer than observed for SN 2011dh, reflecting the differences seen in the I - and U -bands.

5.5. Bolometric evolution

Figure 21 shows the pseudo-bolometric UV to MIR lightcurve for model 12C between 0 and 100 days as compared to observations of SN 2011dh. As for the broad-band lightcurves, the model bolometric lightcurve is not a perfect match and is broader than the observed one. This is not entirely surprising as the model was constructed by hand to fit the late nebular evolution, but it might indicate that a lower E/M ratio is needed. On the other hand the mixing of the radioactive ^{56}Ni plays a stronger role when non-thermal ionization is taken into account (see Sect. 5.6), and we leave a further exploration of this, which would require a new grid of models to be constructed, for future work.

5.6. The effect of NLTE

Figures 22 and 23 show the bolometric lightcurve and the spectral evolution of model 12C calculated with JEKYLL with and without non-thermal ionization and excitation. Before 10 days both the bolometric lightcurve and the spectral evolution are very similar, after which they start to differ in several aspects. This turning point coincides with the time when the radioactive energy deposition becomes important outside the photosphere (see

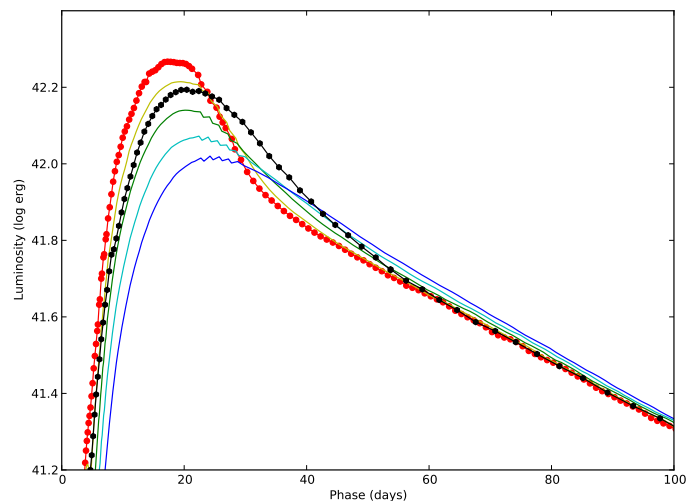


Fig. 20. Bolometric lightcurve for model 12C as calculated with JEKYLL (black circles) and the bolometric lightcurve for model 12C calculated with HYDE using an opacity floor of 0.024 (red circles), 0.05 (yellow line), 0.1 (green line) 0.15 (cyan line) and 0.2 (blue line) $\text{cm}^2 \text{g}^{-1}$.

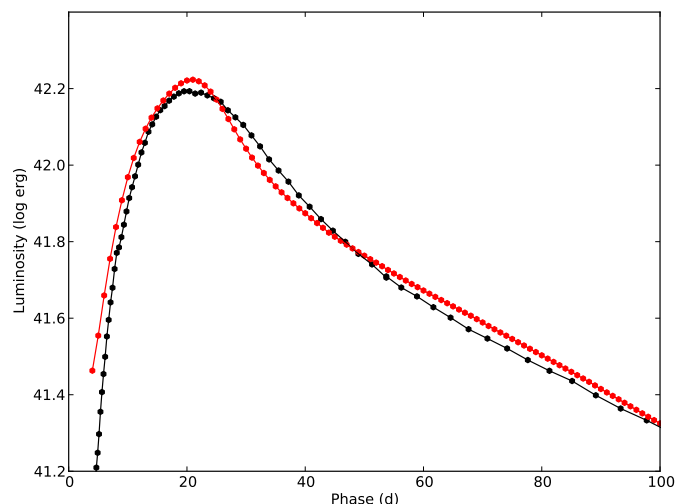


Fig. 21. Pseudo-bolometric UV to MIR lightcurve for model 12C as calculated with JEKYLL (black circles) and the observed pseudo-bolometric UV to MIR lightcurve for SN 2011dh (blue circles).

Fig. 7). The most striking difference in the spectral evolution is the absence of (strong) helium lines in the model without non-thermal ionization and excitation. This well-known effect was originally proposed by Lucy (1991) and has been discussed in some detail by Dessart et al. (2012). Less known is the quite strong effect on the bolometric lightcurve, where the diffusion peak of the model without non-thermal ionization and excitation is considerably narrower. The reason for this seems to be the increased degree of ionization, and therefore the increased electron scattering opacity in the outer region. Contrary to Type Ia SNe (reference), the electron scattering opacity is quite important in shaping the lightcurves of Type IIb SNe, which are therefore sensitive to the degree of ionization. In Fig. 25 we also show a model calculated assuming LTE for the excited levels of the ions (but not for the ionization balance), in a manner similar to what is done by ARTIS. This model shows an even narrower bolometric lightcurve and the reason again seems to be the de-

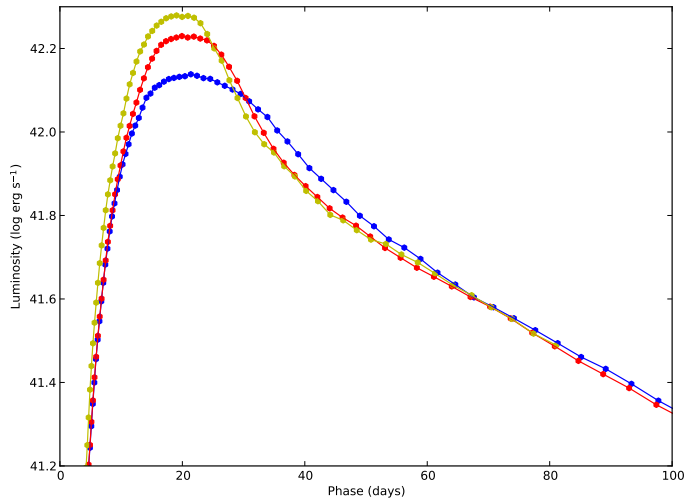


Fig. 22. Bolometric lightcurve for model 12C calculated with (blue) and without (red) non-thermal ionization and excitation. We also show a model assuming LTE for the excited levels (yellow), calculated in a manner similar to ARTIS.

gree of ionization and the electron scattering opacity. In Fig. 24 we show the electron fraction in the three models near peak luminosity, which clearly supports this explanation.

In E15 we calculated the bolometric lightcurve for model 12C with the LTE-based code HYDE, and in Fig. 20 we show this lightcurve together with the one calculated by JEKYLL. HYDE uses opacities calculated for a static medium in LTE, and an opacity floor intended to imitate the effects of expansion and non-thermal ionization. However, the floor was calibrated to the hydrodynamical code STELLA (Melina Bersten, private communication) which does not include non-thermal ionization, so this effect is not taken into account. Comparing the bolometric lightcurves calculated with JEKYLL and HYDE, we see that the latter is considerably narrower, in line with the comparisons discussed above. Furthermore, as also shown in Fig. 20, a good match between the JEKYLL and HYDE calculations is not possible even if the opacity floor is increased, and a more elaborate parametrization of the HYDE opacity is required. In the literature, codes similar to HYDE are commonly used to calculate bolometric lightcurves, and our results highlight the need for full NLTE calculations to properly determine the opacities.

A more detailed discussion on how non-thermal ionization/excitation and other aspects of NLTE affect the observed evolution is outside the scope of this paper and has been postponed to a separate paper.

5.7. The effect of macroscopic mixing

Figures 25 and 26 show the bolometric lightcurve and the spectral evolution of model 12C calculated with JEKYLL using microscopic and macroscopic mixing of the material. Before 15 days both the bolometric lightcurve and the spectral evolution is very similar in the two mixing scenarios, after which the spectral evolution becomes increasingly different. The bolometric lightcurves also differ around the peak, but once on the tail the difference becomes quite modest. The largest differences are seen in the spectral evolution after ~ 40 days. In particular, the Ca II 8498,8542,8662 Å and $[\text{Ca II}]$ 7291,7323 Å lines become much stronger, whereas the $[\text{O I}]$ 6300,6363 Å line becomes much weaker in the microscopic mixing scenario. As was pre-

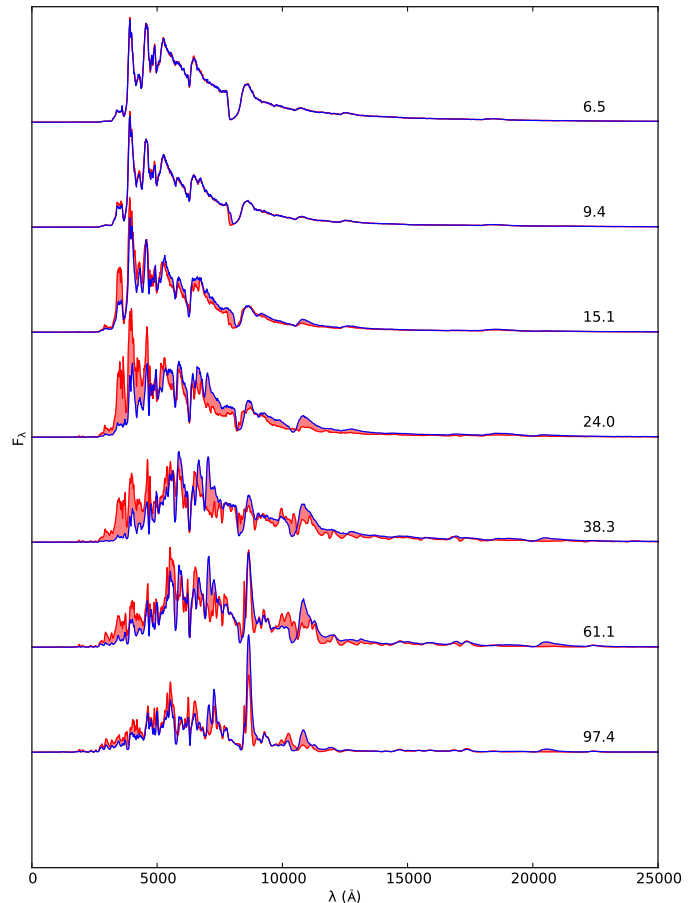


Fig. 23. Spectral evolution for model 12C calculated with (blue) and without (red) non-thermal ionization and excitation.

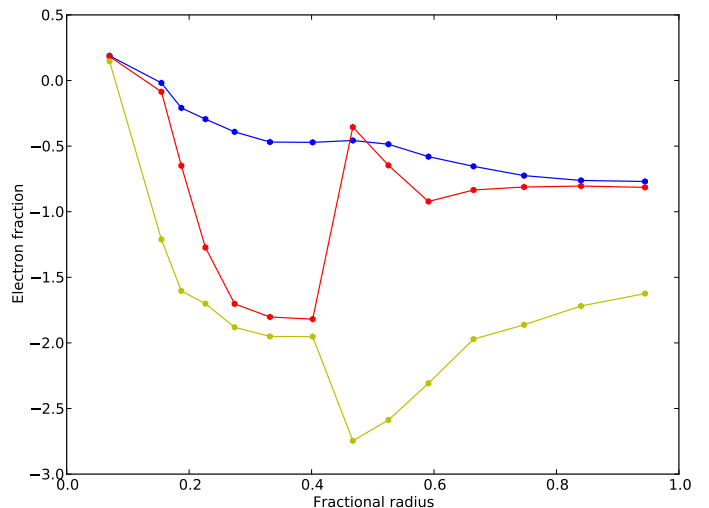


Fig. 24. Electron fraction near peak luminosity (23.5 days) for model 12C calculated with (blue) and without (red) non-thermal ionization and excitation. We also show a model assuming LTE for the excited levels (yellow), calculated in a manner similar to ARTIS.

viously pointed out by Fransson & Chevalier (1989), this effect is caused by microscopic mixing of calcium, which is a very effective coolant, into the oxygen-rich zones. The difference gets even worse after 150 days (not shown), and it seems clear that

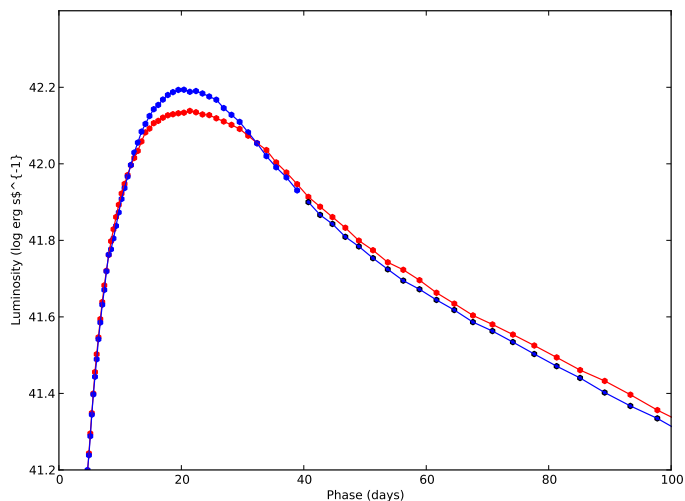


Fig. 25. Bolometric lightcurve for model 12C as calculated with JEKYLL using macroscopic (blue) and microscopic (red) mixing.

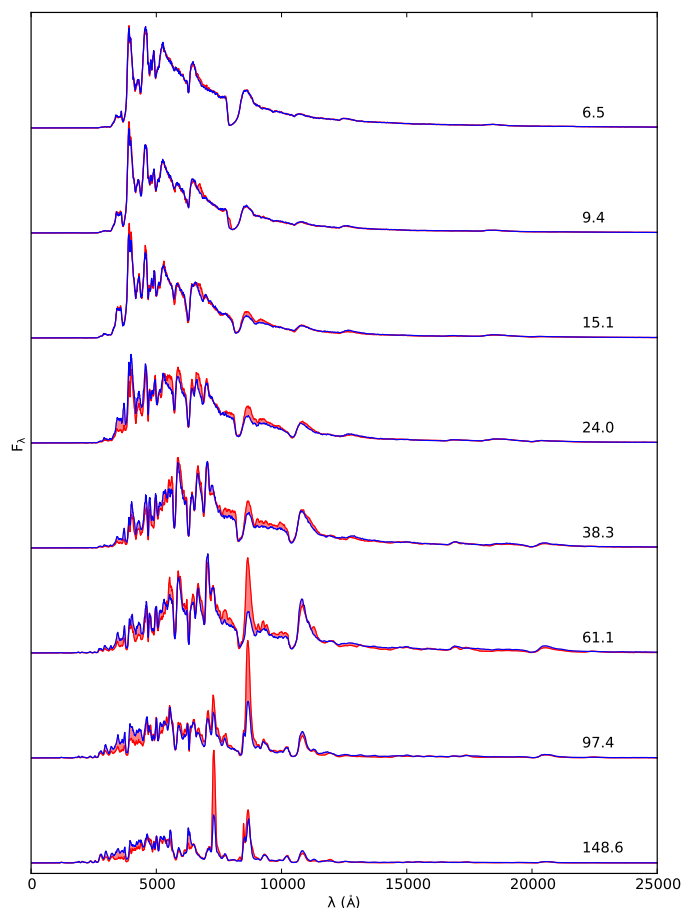


Fig. 26. Spectral evolution for model 12C as calculated with JEKYLL using macroscopic (blue) and microscopic (red) mixing.

macroscopic mixing needs to be taken into account, at least in the nebular phase, for the model to be realistic. A more detailed discussion on macroscopic mixing and the effects of it is outside the scope of this paper and has been postponed to a separate paper.

6. Conclusions

We present and describe JEKYLL, a new code for modelling of SNe spectra and lightcurves. The code assumes homologous expansion, spherical symmetry and steady state for the matter, but is otherwise capable of solving for the time-evolution of the matter and the radiation field in full NLTE. In particular, it includes a detailed calculation of the non-thermal excitation and ionization rates. We also present comparisons with ARTIS and SUMO, two codes that are similar to JEKYLL in some, but not all aspects. The comparisons are done with ARTIS in the photospheric phase and SUMO in the nebular phase, and they both show a good agreement in the observed quantities as well as the state variables.

We have applied JEKYLL to Type IIb SNe, by evolving the preferred J15 model for SN 2011dh through the early phase. This model, which has an initial mass of $12 M_{\odot}$, was previously found to give a good agreement with the nebular spectra (J15) and lightcurves (E15), and here we find a reasonable agreement with the early spectra and lightcurves as well. Some quantitative differences exist, however, and to find a model that improves the agreement is a challenge to be addressed in future works. Nevertheless, most important observational aspects of SN 2011dh, many of which are observed in other Type IIb SNe as well, are well reproduced by the model. It also has much in common with the SE-SNe NLTE models by Dessart et al. (2015, 2016) evolved with CMFGEN, and in particular with the Type IIb model 3p65A. This demonstrates that our understanding of SN 2011dh and Type IIb SNe in general, has reached a rather mature level, and that NLTE modelling of such SNe is capable of producing realistic spectra and lightcurves.

We find strong effects of NLTE as well as macroscopic mixing on the spectra and the lightcurves, which shows that both of these effects are necessary for realistic simulations of SNe. In particular, NLTE effects are strong even on the bolometric lightcurve, which casts some doubts on LTE-based modelling of the bolometric lightcurve commonly used in the literature. For example non-thermal ionization turns out to have a strong effect on the ionization level in the helium envelope, which introduces a coupling between the mixing of the radioactive ^{56}Ni and the diffusion time not accounted for in LTE-based models.

References

- Abbott, D. C. & Lucy, L. B. 1985, *ApJ*, 288, 679
 Bersten, M. C., Benvenuto, O. G., Nomoto, K., et al. 2012, *ApJ*, 757, 31
 Dessart, L., Hillier, D. J., Li, C., & Woosley, S. 2012, *MNRAS*, 424, 2139
 Dessart, L., Hillier, D. J., Woosley, S., et al. 2015, *MNRAS*, 453, 2189
 Dessart, L., Hillier, D. J., Woosley, S., et al. 2016, *MNRAS*, 458, 1618
 Ergon, M., Jerkstrand, A., Sollerman, J., et al. 2015, *A&A*, 580, A142
 Ergon, M., Sollerman, J., Fraser, M., et al. 2014, *A&A*, 562, A17
 Falk, S. W. & Arnett, W. D. 1977, *ApJS*, 33, 515
 Fransson, C. & Chevalier, R. A. 1989, *ApJ*, 343, 323
 Jerkstrand, A., Ergon, M., Smartt, S. J., et al. 2015, *A&A*, 573, A12
 Jerkstrand, A., Fransson, C., & Kozma, C. 2011, *A&A*, 530, A45
 Jerkstrand, A., Fransson, C., Maguire, K., et al. 2012, *A&A*, 546, A28
 Kozma, C. & Fransson, C. 1992, *ApJ*, 390, 602
 Kromer, M. & Sim, S. A. 2009, *MNRAS*, 398, 1809
 Liu, Y.-Q., Modjaz, M., Bianco, F. B., & Graur, O. 2016, *ApJ*, 827, 90
 Lucy, L. B. 1991, *ApJ*, 383, 308
 Lucy, L. B. 2002, *A&A*, 384, 725
 Lucy, L. B. 2003, *A&A*, 403, 261
 Lucy, L. B. 2005, *A&A*, 429, 19
 Marion, G. H., Vinko, J., Kirshner, R. P., et al. 2013, *ArXiv e-prints*
 Maund, J. R., Fraser, M., Ergon, M., et al. 2011, *ApJ*, 739, L37
 Mazzali, P. A. & Lucy, L. B. 1993, *A&A*, 279, 447
 Shull, J. M. & van Steenberg, M. 1982, *ApJS*, 48, 95
 Stritzinger, M. D., Taddia, F., Burns, C. R., et al. 2017, *ArXiv e-prints*
 Taddia, F., Sollerman, J., Leloudas, G., et al. 2015, *A&A*, 574, A60

- Taddia, F., Stritzinger, M. D., Bersten, M., et al. 2017, ArXiv e-prints
- Verner, D. A., Ferland, G. J., Korista, K. T., & Yakovlev, D. G. 1996, ApJ, 465, 487
- Verner, D. A. & Yakovlev, D. G. 1995, A&AS, 109, 125
- Woosley, S. E., Eastman, R. G., Weaver, T. A., & Pinto, P. A. 1994, ApJ, 429, 300
- Woosley, S. E. & Heger, A. 2007, Phys. Rep., 442, 269