Research Plan

The progenitors of CC SNe

What are the progenitor stars of core-collapse (CC) supernovae (SNe)? In spite of observational and theoretical advancements in the field this basic question is still, in many aspects, unsolved. Much of the work in Paper I-VI has been devoted to this issue, and in the near future I hope to advance this work further. Paper I-V focused on the nearby Type IIb SN 2011dh (PTF11eon), and using hydrodynamical lightcurve modelling, nebular spectral modelling and stellar evolutionary progenitor analysis, the progenitor star was found to have a relatively low initial mass (12 solar masses). The analysis is extended to a sample of Type IIb SNe in Paper VI, where a grid of hydrodynamical SN models is used to fit the observations. Most SNe are found to have initial masses below 15 solar masses (see Fig. 1), suggesting that Type IIb SNe lose their hydrogen envelopes due to binary interaction rather than through stellar winds. Understanding the nature of SN progenitors has been my main research interest since I began my PhD, and I see good opportunities to continue this work in Stockholm. In particular, the involvement in the NUTS as well as the Palomar Transient Factory (PTF), allows for studies of large samples or well-observed individual SNe, using the state-of-the-art modelling tools JEKYLL and HYDE that I have developed. Below I briefly describe these tools and the systematic method for sample studies presented in Paper IV. I also discuss the important role of automated SN surveys and finally I present and briefly discuss a number of possible science cases.

The modelling tools.

Understanding the origin of SNe requires physical models advanced enough to reliably reproduce what we observe. With this in mind I have spent the last years focusing on the development of such models, and the combination of the hydrodynamical code HYDE, the radiative-transfer code JEKYLL and the public stellar-evolutionary code MESA (Paxton 2011, 2013, 2015), should full-fill this purpose reasonably well.

JEKYLL has the ability to model <u>both</u> spectra and lightcurves in <u>both</u> the photospheric and nebular phase, taking into account all relevant physical processes. In this respect it can only be rivalled by CMFGEN (Hillier 1990, 1998), which has been used in a number of papers to model the time-evolution of CC SNe (e.g. Dessart et al. 2011, 2012, 2015). JEKYLL is time-dependent (with respect to the radiation field) given the assumption of homologous expansion, solves for thermal and statistical equilibrium, and similar to ARTIS (Kromer 2009), it is based on the Monte-Carlo method developed by Leon Lucy (2002, 2003, 2005). However, contrary to ARTIS, JEKYLL includes all relevant processes in a full solution of the thermal and statistical equilibrium equations. In particular, JEKYLL incorporates the Kozma & Fransson (1992) Spencer-Fano solver to calculate the heating, ionization and excitation rates by non-thermal electrons, which is crucial for calculations of realistic spectra in the nebular phase. Except for the basic tests made by Lucy (2003), JEKYLL is the first code exploring the full NLTE-capabilities of his method. Several improvements where necessary, but the basic idea, where the matter-radiation (lambda) iteration is accelerated by enforcing the constraints of energy conservation and statistical equilibrium on the radiation field, remains the same. The main limitations are the assumptions of spherical symmetry and equilibrium for the gas, both of which could be removed as part of the modelling project. JEKYLL is currently in a mature test phase and an example calculation for a 15 solar mass Type IIP-like model is shown in Fig 4. The code shows good agreement with both CMFGEN and the nebular phase code SUMO (Jerkstrand et al. 2011), and I expect it to be ready for production runs during spring 2017. A previous, less advanced version of JEKYLL (similar to TARDIS, Kerzendorf 2014), was presented in my PhD thesis

HYDE has the ability to model the explosion of a star in spherical symmetry and the bolometric lightcurve of the SN that follows. The code assumes the diffusion approximation to apply throughout the ejecta, and is similar to SNEC (Morozova, 2015). As an example, a sequence of SN models for a 15 solar mass star gradually stripped of its hydrogen envelope is shown in Fig 2., well reproducing the observed lightcurves types for the IIP-IIL-IIb-Ib sequence of SN types. Lately, a new version where the radiative transfer in the optically thin region is solved for correctly has been developed, and this is the version I intend to use in the future.

Combining the codes into **JEKYLL & HYDE** allows for modelling of SNe from the explosion into the nebular phase based on a model for the progenitor stars. To construct such models I use the public stellar evolutionary code MESA. Note that the latest version of this code (Paxton 2015) has the hydrodynamical capability needed to calculate the explosive nucleosynthesis occurring when the shock propagates through the core,. This affects the abundances in the inner parts of the ejecta, which is particularly important when evolving models into the (transparent) nebular phase.

A systematic method

In Paper VI I introduce a method to characterize the progenitor stars of CC SNe based on large samples of SNe, modelled with advanced techniques in a more systematic way than has previously been done. To achieve this, grids of models are evolved from proto-star to SN using MESA and HYDE, and the models are compared to observations to infer the progenitor characteristics (see Fig. 3). In the paper, it is demonstrated that the method is feasible using much more advanced techniques than have been used in previous sample studies (e.g. Lyman et al 2014), which typically use simplified Arnett (1982) like SN models.

Several improvements of the method used in Paper VI are possible, and JEKYLL & HYDE would allow for more accurate physics and a fit of both lightcurves and spectra to the models. The downside is the computational cost, but tests indicate that sufficiently large grids of models should be possible to construct without cutting down too much on the sophistication. Fits to nebular phase models are particularly useful, as this provide an additional constraint on the initial mass from the amount of synthesized material in the ejecta (e.g. Jerkstrand et al 2014).

The role of SN surveys

Modern automated SN and transient surveys are discovering SNe at an unprecedented rate, and are changing the way we study these phenomena. It is a revolution, not only in quantity, but also in quality, and the early discovery and the well-sampled lightcurves provides an excellent foundation for successful modelling. In addition, the selection bias targeted studies have suffered is removed, which allows for the discovery of new types of SNe and transients. A good example is the super-luminous SNe, which tend to occur in faint dwarf galaxies not part of the selection used in previous surveys.

The method described in Paper VI is developed with SN surveys specifically in mind, naturally applies to large numbers of SNe, and provides a way to take advantage of the increasing amount of data. On the other hand, the related increase in quality, allows for improved in-depth studies of individual SNe, and the expanding zoo of new SN types allows for new physics to be explored. Which path is most fruitful may be discussed, but it is clear that the automated SN surveys hos opened a wealth of possibilities to deepen our understanding of SNe.

The NUTS is a fast response follow-up program for ASAS-SN, an automated all-sky survey aimed to discover the nearby/bright SNe as early as possible. This ensures that any nearby/bright SN can be followed in great detail from explosion into the nebular phase with the NOT and other facilities, and allows for in-depth studies of these SNe using JEKYLL & HYDE in a way similar to what was done for SN 2011dh in Paper I-VI. Thanks to the quality of the data and the sophistication of the models, this study was very successful in revealing the nature of the explosion and the progenitor star.

Science cases

A wide range of interesting science cases exists, both samples studies and in-depth studies of individual SNe of particular interest. A natural extension of the work on Type IIb SNe in Paper IV, would be studies of the similar Type Ib and Ic SNe, which could add to the growing evidence that also these SNe originate mainly from the binary population. Other interesting topics with respect to stripped envelope (Type IIb, Ib and Ic) SNe, are the distribution of the radioactive nickel, and the amount of helium and hydrogen left in their envelopes.

Another related class of SNe are the Type IIL, which have been suggested to originate from progenitors intermediate between those of Type IIb and IIP SNe. However, the amount of modelling in the literature is very restricted, so this issue is far from settled. Using JEKYLL & HYDE a grid of detailed models could be constructed to explore if this scenario is consistent with the lightcurves and spectra we observe.

The super-luminous SNe were discovered quite recently, and their physical origin is unclear and have been much debated. The most popular powering scenarios for these extremely luminous objects are circum-stellar interaction or heating from a down-spinning and highly magnetized neutron star (magnetar), although powering by radioactive decays is not excluded. JEKYLL & HYDE offers the possibility to model the entire evolution of well-observed super-luminous SNe in unprecedented detail, which could help to discriminate between these scenarios.

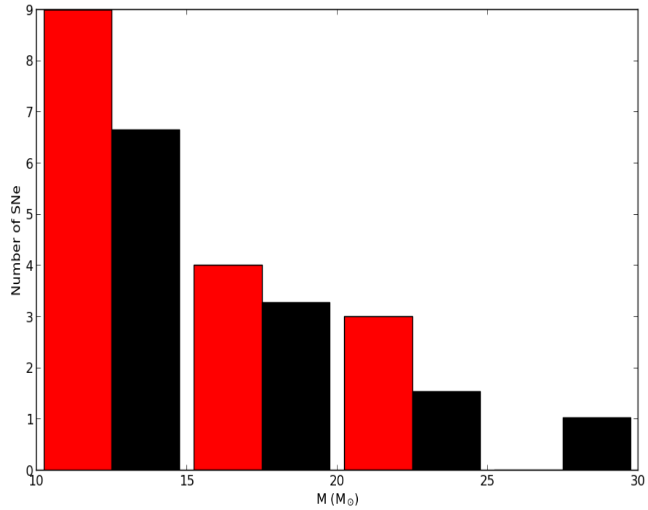

Fig 1: Initial masses for a sample of Type IIb SNe (red) determined by fits to the model grid, as compared to a standard Salpeter IMF (black). (Paper VI / PhD Thesis).

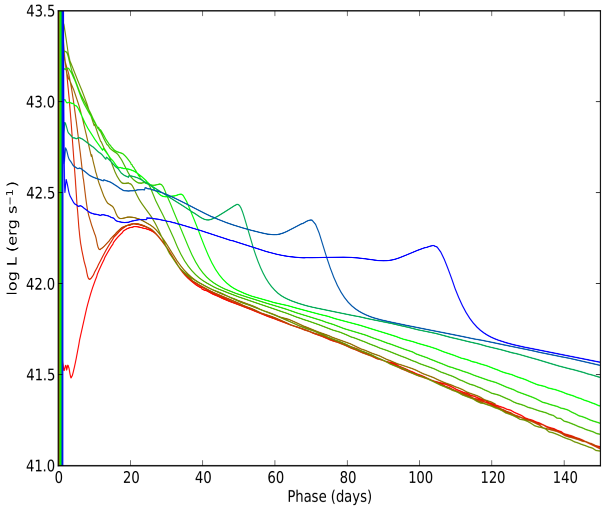

Fig 2: Bolometric lightcurves calculated with HYDE for a 15 solar mass star gradually (blue to red) stripped off its hydrogen envelope. (Paper VI / PhD Thesis).

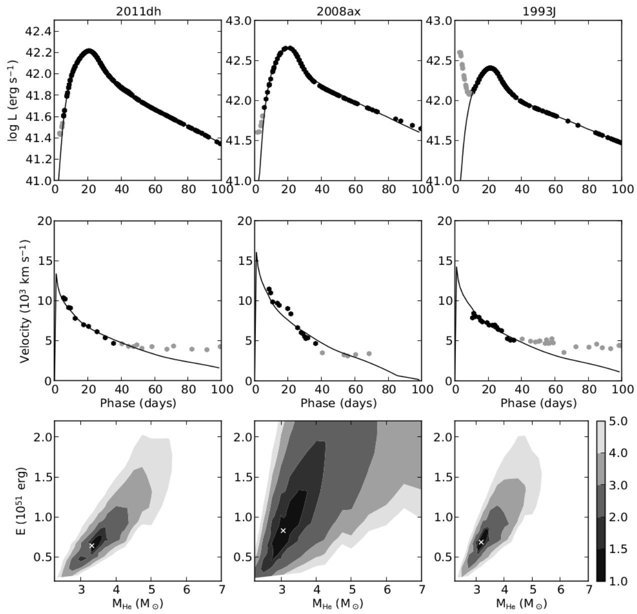

Fig. 3: Bolometric lightcurves (upper panels) and photospheric velocities (middle panels) for the best-fit models of SN 2011dh (left panel), 2008ax (middle panel) and 1993J (right panel). (Paper VI / PhD Thesis)

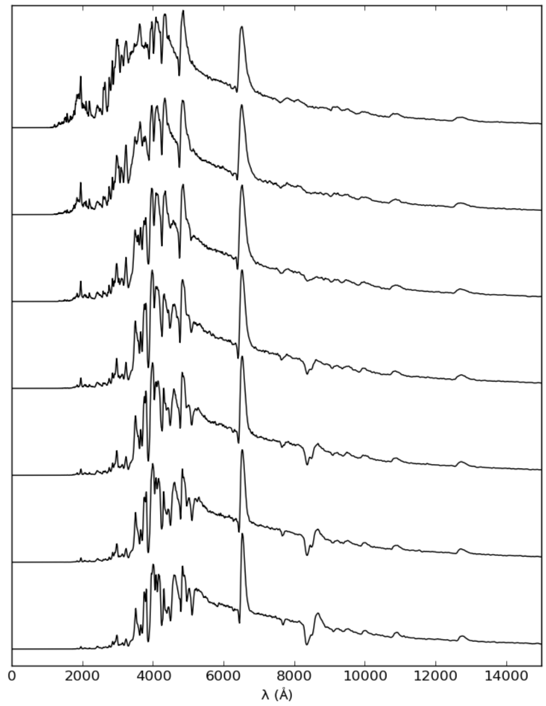

Fig. 4: Spectral evolution (28-56 days) calculated with JEKYLL for a 15 solar mass Type IIP-like model.