Research Plan

After discussing with Stuart Sim I propose to focus the work on two different (but related) subjects;

1) Development of the ARTIS code to support modelling of nebular spectra.
2) Studies of the progenitors of core-collapse (CC) supernovae (SNe) using the hydrodynamical and multi-method approaches described below.

The first subject extends on my own work on photospheric spectral modelling (Paper II) and that together with Anders Jerkstrand on nebular spectral modelling (Paper IV and V). The photospheric Monte-Carlo (MC) code used in Paper II was developed by me and is similar to the one by Mazzali & Lucy (1993), whereas the MC based nebular code used in Paper IV and V was developed by Anders Jerkstrand. Although I have not contributed to the latter code I have become well acquainted with the basic principles for nebular spectral modelling. The further developments of the Mazzali & Lucy (1993) method by Lucy (2002,2003,2005) and Kromer & Sim (2009) used in ARTIS is a bit beyond my current knowledge, however, and I would probably need to read up on these papers. On the other hand, I am a computer programmer by profession (see CV), which I think could be a great benefit in this work. The second subject extends on my work on the progenitor of CC SNe in Paper I-VI, and in particular on the use of hydrodynamical model grids in Paper IV and VI, and below I discuss the second subject in some more detail, as well as a number of concrete science cases.

The progenitors of CC SNe

What are the progenitor stars of CC 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 (few-years) 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. Previous sample studies like Lyman et al. (2014) use approximate methods (e.g. Arnett 1982), and the use of a hydrodynamical model grid based on evolutionary stellar models greatly improves the reliability of the results.

My first priority would be to develop the hydrodynamical model grid further and to apply it to samples of SNe of other types, in particular Type Ib, Ic and IIL SNe. The progression of SN types IIP-IIL-IIb-Ib-Ic is commonly thought to reflect the continuous stripping of the hydrogen and helium envelopes off the progenitor stars (see Fig. 2), but how the mass is lost is less clear, and could be either through stellar winds or by Roche-lobe overflow in binary systems. Particularly interesting is the increasing evidence that not only Type IIb, but also Type Ib and Ic SNe, may originate mainly from the binary population. My second priority would be to further develop the multi-method approach used in Paper I-V. This method requires collaboration, but given the expertise in Belfast on both nebular spectral modelling and progenitor analysis, the prospects for doing such work seems to be good. Nebular R-band modelling, which is the poor-man's version of nebular [OI] 6300,6364 Å modelling (see below), is a particularly promising idea to explore, that would allow the nebular method to be applied to larger samples of SNe. Finally, the methods described could also be applied to thermonuclear SNe and conversely, ARTIS could be applied to CC SNe, so further possibilities exists that could be explored.

The hydrodynamical model grid

The use of hydrodynamical model grids to determine the progenitor characteristics has been explored before (e.g. Litvinova & Nadezhin 1983, 1985) with somewhat mixed results (e.g. Hamuy 2003), but the decreasing computational cost and the increasing amount of data obtained by surveys like Pan-STARRS and PESSTO, motivate a renewed interest in this approach. In Paper VI the hydrodynamical code HYDE is used to construct a grid of SN models based on bare helium cores evolved with MESA STAR (Paxton et al. 2011), and in Paper IV and VI this grid is used to fit the bolometric lightcurves and photospheric velocities of SN 2011dh and a sample of Type IIb SNe, respectively. The grid consist of more than 10000 models parametrized by the helium core mass, the explosion energy and the mass and distribution of the radioactive nickel. Although the method is superior to approximate lightcurve modelling (e.g. Arnett 1982), there is a number of simplifications involved and further development of the method would be one of my priorities. For example the treatment of lines opacities and the optically thin region could be improved following e.g. Blinnikov et al. (1998). Use of spectral Monte-Carlo modelling (Paper II) to better estimate the photospheric velocities, is another potential improvement. Finally, expanding the grid with additional parameters would widen the range of applicability (see below).

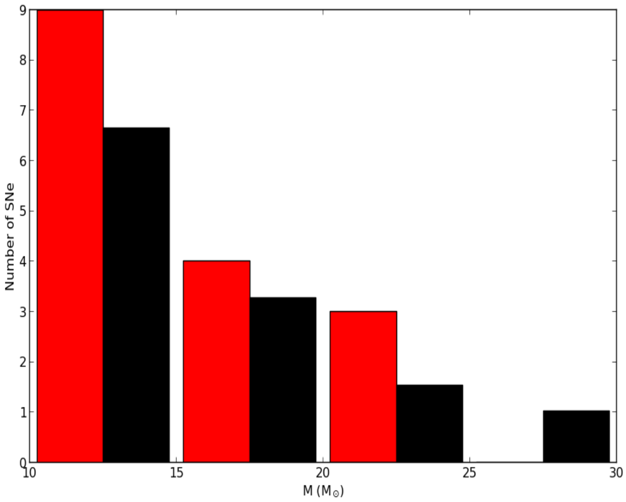

Fig 1 : Initial masses for a sample of Type IIb SNe (red) determined by fits to the model grid, as compared to a standard Salpeter IMF (black) (from Paper VI).

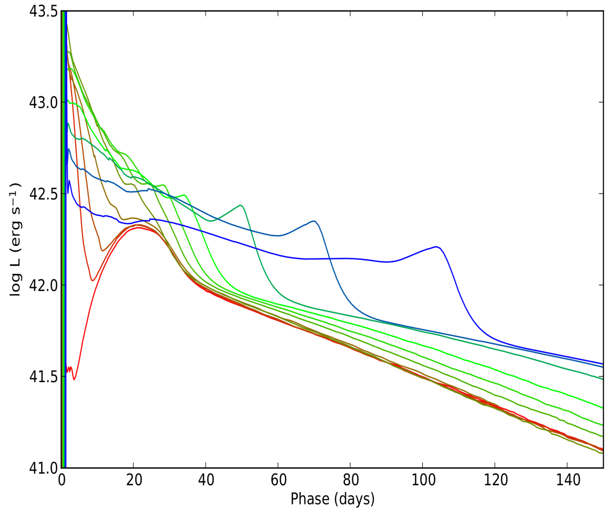

Fig 2: Bolometric lightcurves calculated with HYDE for a 15 solar mass star gradually (blue to red) stripped off its hydrogen envelope (from Paper VI).

Multi-method modelling

In Paper I-V hydrodynamical lightcurve modelling, nebular spectral modelling and stellar evolutionary progenitor analysis are used to determine the characteristics of the progenitor star for SN 2011dh, which gives a confidence in the obtained results otherwise not possible. Such investigations require cooperation between scientists with different expertise, and during my PhD I have established a close collaboration with the Belfast group, in particular with Anders Jerkstrand (nebular spectral modelling) and Justyn Maund (progenitor analysis). Nebular spectral modelling and progenitor analysis provide estimates of the initial mass of the progenitor star by comparisons of the abundances of heavy elements (e.g. oxygen), and the progenitor luminosity, respectively, to stellar evolutionary models. Hydrodynamical modelling, on the other hand, can only well constrain the ejecta mass (except in the case of Type IIb SNe). Progenitor detections are only possible in the most nearby galaxies, whereas nebular spectral modelling is feasible for SNe at somewhat larger distances. A poor-man's version of the nebular method using R-band photometry exists, however, as the flux of the [OI] 6300,6364 Å line, which is very sensitive to the initial mass (Paper V), falls within this band. Another interesting multi-method approach is to combine the hydrodynamical model grid with a bolometric correction (BC) determined with spectral modelling. This method was used in Paper IV to model the 400 days pseudo-bolometric lightcurve of SN 2011dh (see Fig. 3).

Type Ib SNe

Type Ib SNe likely originate from stars that have lost their hydrogen envelopes, but still retain some of their helium envelopes. Sample studies based on approximate lightcurve modelling (e.g. Cano et al. 2013, Taddia et al. 2014 and Lyman et al. 2014) find rather low ejecta masses, suggesting these SNe to originate mainly from the binary population. Expanding the model grid with a parameter for the helium envelope mass lost, a more elaborate study using hydrodynamical modelling is possible. The literature sample consists of >30 SNe and provides a good starting point for such a work. There will probably be a strong degeneracy between the carbon-oxygen core and helium envelope masses, so that only the ejecta mass, and not the initial mass, can be well constrained. To improve on this the work could be coordinated with modelling of nebular spectra or R-band photometry, through which estimates of the carbon-oxygen core mass as well as the initial mass can be obtained.

Type Ic SNe

Type Ic SNe likely originate from stars that have lost their hydrogen and helium envelopes, but could also originate from helium rich progenitors if the radioactive nickel is buried in the core (Dessart et al. 2011). Taddia et al. (2014) finds extensive mixing of the nickel using approximate methods, supporting the former scenario. Samples studies based on approximate methods (e.g. Cano et al. 2013, Taddia et al 2014 and Lyman et al. 2014) find rather low ejecta masses, similar to those for Type IIb and Ib SNe, suggesting Type Ic SNe to originate mainly from the binary population. In addition, these studies find broad-lined Ic SNe to have higher explosion energies and nickel masses as compared to normal Type Ic SNe, whereas the ejecta masses appears to be similar (but Cano et al. 2013 find higher ejecta masses for the GRB associated SNe). A more elaborate study using hydrodynamical modelling would be most interesting, and using a model grid based on carbon-oxygen cores this is possible. The literature sample consists of >40 SNe and provides a good starting point for such a work.

Type IIL SNe and SN 2009kr

Anderson et al. (2014) find that Type IIP and Type IIL SNe rather represent a continuum of events than two separate classes, which is consistent with the idea that the sequence IIP-IIL-IIb corresponds to the continues stripping of the hydrogen envelope off the progenitor stars. Not much modelling of Type IIL SNe exists in the literature, but Swartz et al. (1991) find a high helium abundance and a low mass of the hydrogen envelope to best reproduce their lightcurves. Expanding the model grid with these parameters this hypothesis could be further investigated. I have reduced a high quality dataset for the Type IIL SN 2009kr which could provide a starting point for such a work. The SN 2009kr dataset includes nebular spectra, so in this case nebular spectral modelling could strengthen the conclusions from the hydrodynamical modelling. A progenitor candidate for SN 2009kr was identified by Fraser et al. (2010) and Elias-Rosa et al. (2010), but the identification has not (yet) been confirmed by its disappearance.

Type IIb SNe

Type IIb SNe likely originate from stars that have lost all but a tiny fraction of their hydrogen envelopes, a fact well established for SNe 1993J (e.g. Woosley et al. 1994) and 2011dh (Paper I-V). A number of possibilities exist to advance the work on Type IIb SNe in Papers I-VI. Expanding the model grid in suitable ways, a study of their hydrogen envelope characteristics, as well as a more elaborate study of the mixing of the radioactive nickel (in particular with respect to the amount of high-velocity nickel, see Paper IV), is possible. Note that Type IIb SNe are unique in that they (likely) consist of almost bare helium cores, and therefore estimates of their initial masses are possible with hydrodynamical modelling (Paper VI). The reliability of these results could be greatly improved, however, by modelling of nebular spectra or R-band photometry, through which independent estimates of the initial masses can be obtained (as was done for SNe 2011dh, 1993J and 2008ax in Paper V).

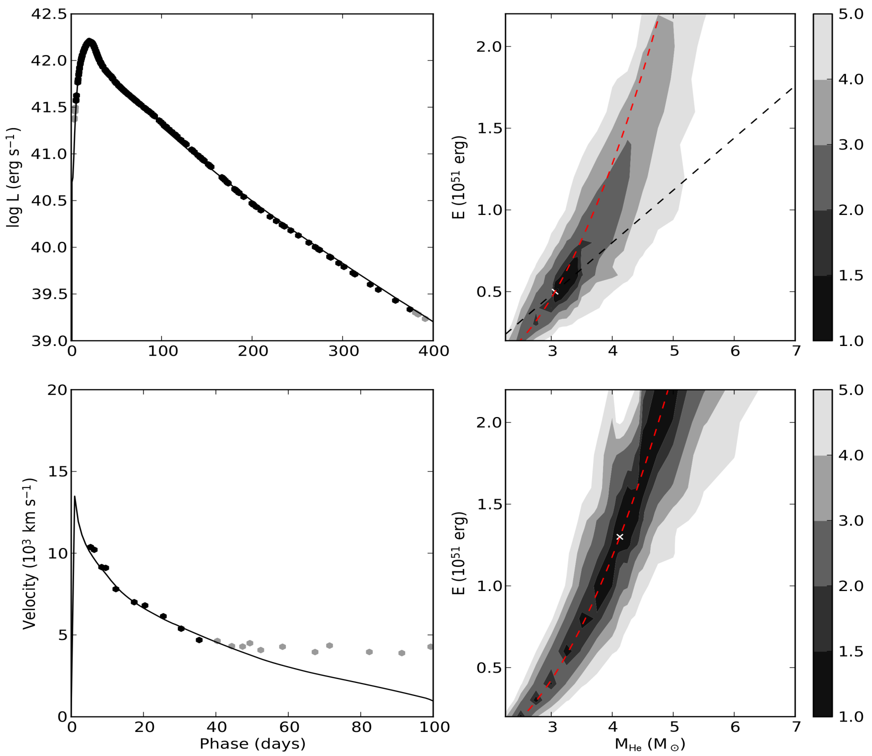

Fig 3 : UV-to-MIR pseudo-bolometric lightcurve (upper left panel) and photospheric velocity evolution (lower left panel) for SN 2011dh as fitted to the hydrodynamical model grid using a BC determined with spectral modelling. The upper right panel shows the normalized standard deviation in the fit projected onto the explosion energy - helium core mass plane (from Paper IV).