Research Plan

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 (few-years) future I hope to advance this work further. Paper I-V focused on the nearby Type IIb SN 2011dh, 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. 2), 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 (CC) SNe of other types, in particular Type Ib and IIL SNe. The progression of SN types IIP-IIL-IIb-Ib-Ic is commonly thought to reflect the continues stripping of the hydrogen and helium envelopes off the progenitor stars (see Fig. 1), 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 SNe, but also Type Ib and Ic, 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 (in particular with respect to nebular modelling, which is beyond my current skills), so the progress is partly outside my control.

Below I discuss the hydrodynamical grid and multi-method approaches in a bit more detail, as well as a number of concrete science cases. Substantial work could be based on literature data, but new data would improve the results and are in some cases required. To obtain new data dedicated programs could be initiated, and I'm particularly interested in what can be achieved using the NOT, which is an excellent telescope to follow nearby SNe, not the least when the new NOT Transient Explorer (NET) is installed in 2017. New observations could also be obtained through existing programs like PESSTO. Much of my previous work have been done within a broad collaboration of European SN scientists, and I think it would be a good idea to continue this cooperation. As pointed out in the cover letter, I have both interest and great experience in reducing data, so in the case new data is obtained I can take care of the reductions whenever needed.

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 the Palomar Transient Factor (PTF) 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). This comes at a cost, however, as the computational time increases in an exponential way.

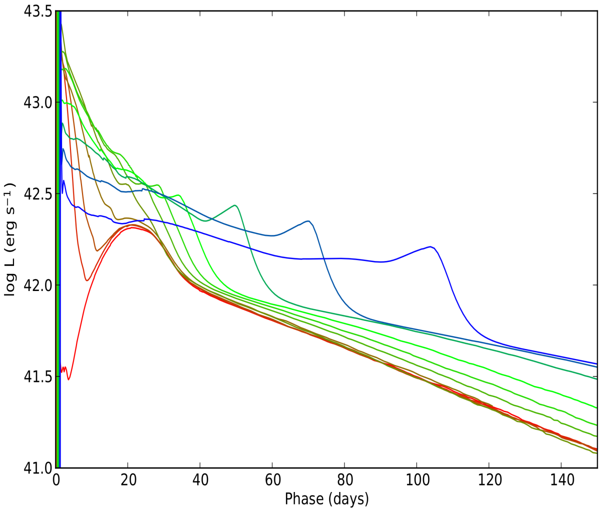

Fig 1: Bolometric lightcurves calculated with HYDE for a 15 solar mass star gradually (blue to red) stripped off its hydrogen envelope (from Paper VI).

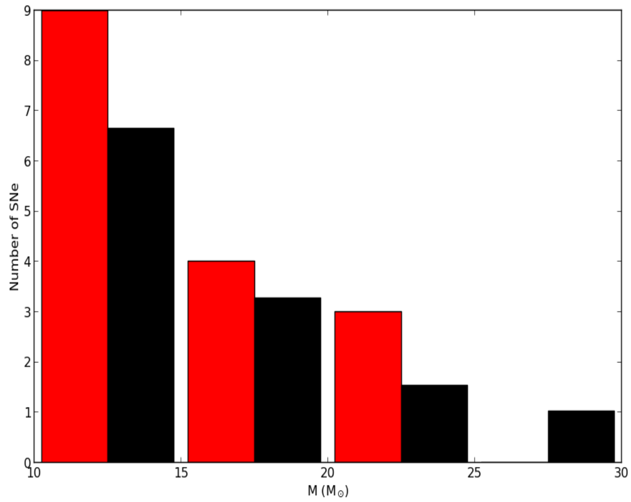

Fig 2 : Initial masses for a sample of Type IIb SNe (red) determined by fits to the model grid, as compared to a standard Salpeter IMF (black) (from Paper VI).

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 nearby galaxies, whereas nebular spectral modelling is feasible for SNe at larger distances. Some SNe fade rather fast, so except if these are nearby nebular spectra *might* require 10-meter class telescopes. A poor-man's version of the 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.

Type Ib SNe

Type Ib SNe likely originate from stars that have lost their hydrogen envelopes, but still retain some of their helium envelopes, and a few sample studies based on approximate lightcurve modelling of ~10 SNe have been published (e.g. Taddia et al. 2014 and Lyman et al. 2014). Expanding the model grid with a parameter for the helium envelope mass lost, a study based on the entire literature sample of Type Ib SNe is possible. Given the recently published Modjazz et al. (2014), Bianco et al. (2014) and Sako et al. (2014), this sample consists of ~35 SNe, although some of these likely need to be excluded due to poor quality. 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, whenever such observations are available. Alternatively a program to obtain photospheric *and* nebular data for Type Ib SNe could be initiated.

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 (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). Combining this with modelling of nebular spectra or R-band photometry the reliability of the results could be considerably improved. As such data are only occasionally available a program to obtain photospheric *and* nebular data could be initiated (see above). In Paper IV strong evidence for formation of CO and dust in the ejecta of SN 2011dh was found. A study of this for other Type IIb SNe would be most interesting, but would require quite demanding late-time near-infrared (NIR) and mid-infrared (MIR) observations, either earth-based or space-based (Spitzer).