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 (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. 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.

The ZTF survey has a number qualities most useful for hydrodynamical lightcurve studies. Good constraints on the explosion epochs are essential, and the early lightcurve carries information about the radius of the progenitor star and the mixing of the radioactive nickel. Furthermore, the ZTF survey also allows for unbiased (or at least less biased) samples of SNe to be collected. I find it particularly interesting to further investigate the Type IIbs with respect to the progenitor radius, to extend the method to other types of SNe, and to study the mixing of the nickel in stripped-envelope 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, but also Type Ib and Ic SNe, may originate mainly from the binary population.

Multi-method modelling, as in Paper I-V, is also interesting, but requires collaboration (in particular with respect to nebular modelling, which is beyond my current skills), so the progress is partly outside my control. Nebular R-band modelling, which is the poor-man’s version of nebular [OI] 6300,6364 Å modelling (see below), is a particularly promising method, that would allow the nebular method to be applied to larger samples of SNe. Below I discuss the hydrodynamical and multi-method approaches in a bit more detail, as well as a number of concrete science cases. Finally, I have great experience in observing and in reducing and calibrating observations of several kinds, and although I have lately moved a bit towards modelling I have a strong interest in the observational side of astronomy. In the choice between the theoretical and observational side I chose to be in the middle, as this is really where the action is.

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 PTF/ZTF, 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.

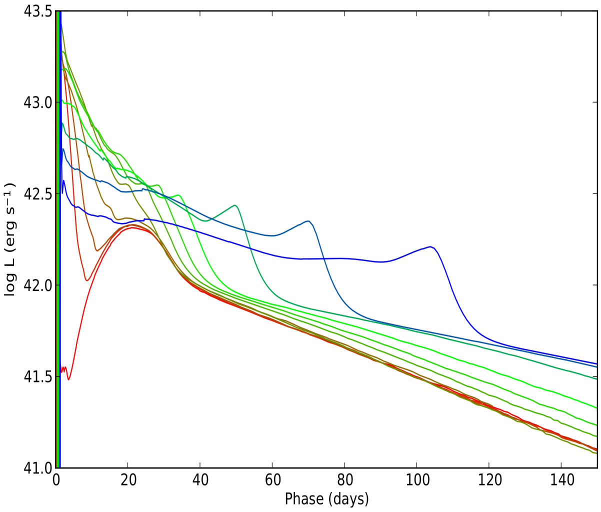

Fig 1: Bolometric lightcurves calculated with HYDE for a 15 solar mass star gradually (blue to red) stripped off its hydrogen envelope (from Paper VI).

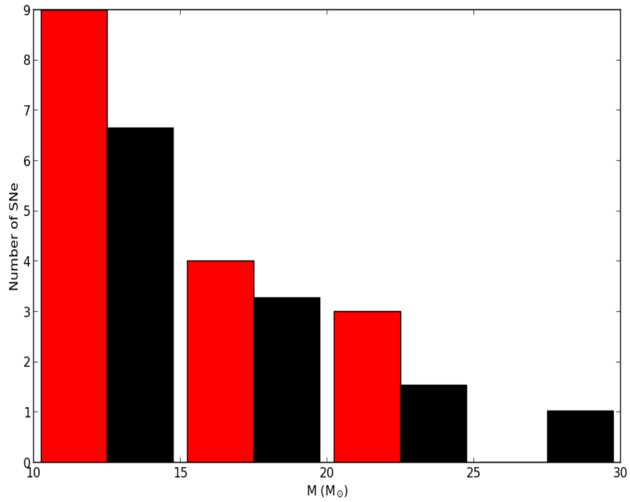

Fig 2 : Initial masses for a sample of Type IIb SNe (red) determined by fits to the model grid, as compared to a standard Salpeter IMF (black) (from Paper VI).

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 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.

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, parameter studies of Type Ib SNe are possible. There will probably be a strong degeneracy between the CO 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. Given the recently published Modjazz et al. (2014), Bianco et al. (2014) and Sako et al. (2014), the literature sample consists of ~35 SNe and provides a good starting point. Building a ZTF sample, with early coverage and well constrained explosion epochs, would improve the reliability of the results considerably, and could also be combined with a program to obtain nebular spectra or R-band photometry.

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.

The hydrogen envelopes of 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). The characteristics of the hydrogen envelopes are less known, but for SNe 1993J and 2011dh they were found to be quite extended (several hundred solar radii) by hydrodynamical modelling of the early decline in the lightcurve (Woosley et al. 1994 and Paper II). The Type IIb sample study in Paper VI is based on bare helium core models, and do not model the hydrogen envelope characteristics, but expanding the model grid in suitable ways, such a study is possible. However, only a few Type IIb in the sample have the early coverage and the constraints on the explosion epochs needed, and the ZTF survey would be ideal to collect a new sample, or complementing the existing one.

The nickel mixing in stripped-envelope SNe

Stripped-envelope (Type IIb, Ib and Ic) SNe are mainly powered by the heating from the radioactive nickel, and the rise to peak luminosity is sensitive to the mixing of this nickel, in turn determined by hydrodynamical instabilities in the explosion. 1-D hydrodynamical modelling prohibits these instabilities, so the mixing of the nickel is treated as a free parameter, mainly constrained by the rise to peak luminosity. The amount of mixing is, in turn, important for the excitation of the helium lines, and if the nickel resides deep in the ejecta the SN might show a Type Ic signature even if the ejecta is helium rich (Dessart et al. 2011). In Paper VI we find extensive mixing of the nickel required for Type IIb SNe with early coverage and well-constrained explosion epochs, and a similar conclusion is reached for Type Ic SNe by Taddia et al. (2014). Collecting a ZTF sample of stripped-envelope SNe with early coverage and well-constrained explosion epochs would make a more detailed investigation of the mixing of the nickel in stripped-envelope SNe possible. This requires expansion of the model grid for Type Ib (see above) and Ic SNe, and using a more elaborate parametrization the finer details of the nickel distribution could also be investigated (e.g. the fraction of high-velocity nickel needed to reproduce the lightcurve, see Paper IV).