From Interacting Binaries to Exoplanets: Essential Modeling Tools
Proceedings IAU Symposium No. 282, 2011
Mercedes T. Richards & Ivan Hubeny, eds.

doi:10.1017/S1743921311027463

Modeling Supernova Spectra

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Abstract. We highlight results from a series of investigations into modeling spectra of core-collapse supernovae (SNe). We have explored the accuracy of the expanding-photosphere method, and found that it can be used to obtain distances to Type IIP SNe with an accuracy of $\lesssim$10%. We confirm the result of Utrobin and Chugai (2005) that time-dependent terms must be included in the statistical equilibrium equations in order to model H I line evolution in Type II SNe, and show that time-dependent terms influence other spectral features (e.g., He I lines). We have initiated a study of polarization signatures from aspherical but axially-symmetric Type II SN ejecta. Hillier and Li acknowledge support from STScI theory grant HST-AR-11756.01.A and NASA theory grant NNX10AC80G. Dessart acknowledges financial support from grant PIRG04-GA-2008-239184.

Keywords. stars: supernovae general – stars: supernovae individual (SN 1987A, SN 1999em) – stars: distances – radiative transfer

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With the advent of blind wide-angle surveys, supernova (SN) research is poised to make huge advances. These surveys will discover thousands of SNe, potentially identifying new subtypes, and affirm their relative occurrence versus class and host galaxy properties. In addition, forthcoming large-aperture telescopes will facilitate the direct identification of SN progenitors and provide spectral monitoring of SNe throughout their temporal evolution. With these new observations comes the need for theoretical advances in modeling SN spectra. Over the last several years, we have improved our radiative transfer code, CMFGEN, so that we can accurately model the formation of SN spectra.

Initially we modeled SNe as we would a stellar atmosphere. That is, we ignored time-dependent terms, imposed a lower boundary condition and adjusted this boundary condition, and photospheric abundances, until our model spectrum matched that observed. We explored the physics of continuum and line formation in Type II SNe (Dessart & Hillier 2005b). Additionally, we explored the accuracy of the expanding-photosphere method (EPM) and related techniques to determine distances to the host galaxies of Type II SNe. We showed that accurate distances to SNe could be obtained using the EPM technique, although there were several sources of inaccuracies which could affect distance determinations (Dessart & Hillier 2005a). Using spectral fitting, rather than photometry, overcomes many of these limitations (see also Baron *et al.* 2004).

A problem with our early investigations was that we could not match the Hα line strength during the recombination epoch – the model Hα was always weaker and narrower than observed. Following a suggestion by Utrobin & Chugai (2005), we explored the effect of time-dependent statistical equilibrium calculations. We showed that time-dependent terms substantially influence the strength of Hα during the recombination epoch, and their inclusion allows much better agreement of spectra with observation for the Type IIP

SN 1999em (Dessart & Hillier 2008). Later, we confirmed the work of Utrobin & Chugai (2005) that time-dependent statistical equilibrium calculations allow us to accurately model the He I and H I lines in SN 1987A (Dessart & Hillier 2010). As the time-dependent term changes the H ionization state, and hence the electron density, lines of other species, such as the Na I D lines, are also influenced.

As SNe are inherently time-dependent phenomena, we improved CMFGEN so that we could undertake fully time-dependent radiative transfer modeling of SN ejecta. We now start all our simulations on full SN ejecta resulting from radiation-hydro explosion models of physically-consistent pre-SN star evolution models. This approach allows a direct confrontation of synthetic observables with ejecta and progenitor properties, and thus provides constraints on the progenitor star. Using this technique, we modeled the spectral evolution of SN 1987A, and found superb agreement with observation (Dessart & Hillier 2010). The modeling was based on the hydrodynamical model lm18a7Ad (Woosley, priv. comm.), and contained *no* free parameters. We then applied the technique to explore spectral formation for two RSG progenitors which produce classic Type IIP SNe. Our models, while showing strong spectral similarities to observations, suggested that the initial radii of the two RSG models were too large (Dessart & Hillier 2011a).

We applied the fully time-dependent technique to a sample of Type Ib/Ic SN models (Dessart *et al.* 2011), and confirmed that most Type Ib/Ic SNe come from low mass progenitors. While trace amounts of hydrogen can be readily detected in early spectra of Ib/Ic SNe, helium may not be seen even if it makes up 50%, by mass, of the outer ejecta. This occurs because of the low effective temperature and the high ionization energy of He I. Eventually ionizations by non-thermal electrons, produced from the decay of high energy electrons, might excite He I lines (Lucy 1991). Thus we have incorporated non-thermal processes into CMFGEN. Such processes are also important for producing nebular-phase Type II SN spectra.

Hydrodynamical simulations of core-collapse SNe suggest that they are inherently 3D. Observational polarization studies support this scenario as most core-collapse SNe show intrinsic polarization. In order to investigate the constraints polarization places on the geometry of SN ejecta we have studied polarization signatures from axially-symmetric Type II SN ejecta (Dessart & Hillier 2011b). At early times, before the end of the plateau stage, we find that strong cancellation effects inhibit a large polarization, even when the intrinsic asymmetry is large. Further, the polarization can show a strong wavelength dependence, and even show 90° changes in the polarization angle. Similar effects can occur across strong lines such as Hα. Interestingly, our results indicate that even with constant asymmetry, a large change in the magnitude of the polarization can occur at the end of the plateau phase. Usually, this has been thought to indicate that the H-rich envelope is roughly spherically symmetric, while the He core has strong asymmetries.

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https://doi.org/10.1017/S1743921311027463 Published online by Cambridge University Press