Model atmospheres for type Ia supernovae: Basic steps towards realistic synthetic spectra

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1.1 Introduction

Analyses and interpretations of the meanwhile enormous database of excellent spectra of type Ia supernovae obtained in key projects and extensive searches still suffer from missing realistic numerical simulations of the physics involved. One of the most important steps towards this objective concerns a detailed simulation of the radiative transfer in the outermost parts of this objects in order to calculate synthetic spectra on the basis of models of the explosion scenario. The priority objective thereby is to construct for the first time consistent models which link the results of the hydrodynamics and nucleosynthesis obtained from the explosion models (see, for example, [7], [8], these proceedings) with the calculations of light curves (see, for instance, [1],[9], these proceedings) and synthetic spectra of SN Ia. After a phase of testing this new tool will provide a method for SN Ia diagnostics, whereby physical constraints on the basic parameters, the abundances, and the hydrodynamic structures of the atmospheric part of the objects can be obtained via a detailed comparison of observed and synthetic spectra. This will also allow to determine the astrophysically important information about the distances of SN Ia.

First results in this direction are presented in Section 1.3. In the preceding sections we will first with regard to our objective briefly summarize the most important observed properties of type Ia supernovae, and then discuss the current status of our treatment of the hydrodynamic expanding atmospheres of SN Ia.

1.2 Observed properties of type Ia supernovae

The classification of supernovae is based on purely empiric observational properties. In this scheme, type Ia supernovae are defined by the absence of hydrogen and helium spectral lines and a strong absorption feature of Si II lines near 6100 Å in epochs around maximum light. In late phases the SN Ia spectra are dominated by emission of forbidden lines of mainly iron and cobalt.

Prominent features in the early-time spectra of type Ia supernovae – this is the phase we want to analyze at present – are characteristic absorption lines resulting from low ionized intermediate-mass elements (such as Si II, O I, Ca II, Mg II). The formation of these lines results in a pseudo-continuum that is set up by the overlap of thousands of these lines. The absorption lines show characteristic line shapes due to Doppler-broadening resulting from large velocity gradients. In the UV-part of the spectrum, the flux is strongly depleted (compared to a blackbody-fit in the optical range) by line blocking of heavy element lines (especially Fe, Co, Mg). Towards the red and IR, the flux is also low due to the absence of significant line influence in these regions. Towards later phases (~ 2 weeks after max.), heavier element lines become more prominent as the photosphere recedes deeper into the ejecta. At this time emission features also start to increasingly dominate the spectral characteristics. In the nebular phase ($\sim$ 1 month) the spectrum approaches a typical nebular appearance dominated by lines of heavy element forbidden transitions.

The spectra as well as the light curves of type Ia supernovae show a high degree of homogeneity; however, some intrinsic differences are also observed. The mechanisms leading to these differences have to be understood in order to draw conclusions based on the homogeneity, such as the distance measurements for cosmological applications. (For detailed reviews of the optical properties of SN Ia we refer to [3],[2].)

1.3 Model atmospheres for type Ia supernovae

In early phases, which are considered here, a supernova of type Ia is described by a photosphere in the deeper layers (i.e., the sphere where the optical depth $\tau = 1$) and a superimposed extended atmosphere that expands at high velocities – up to 30000 km/s.

Due to the high radiation energy density and the dominant role of scattering processes the problem we are dealing with is strongly non-local, leading to typical conditions that make consideration of NLTE (non local thermodynamic equilibrium) effects necessary. Additionally, processes of line blocking and blanketing significantly influence the radiative transfer within the ejecta and thus the observed spectral properties (see [5]). This behavior results in the strong depletion of the flux in the UV part and the blue region of the spectrum due to the influence of thousands of lines of the heavy elements. As the absorbed radiation is partly reemitted towards lower layers ("*backwarming*") the temperature structure is also affected, and in turn the ionization equilibrium and thus the radiation field itself.

Certain properties of supernovae make the full problem of NLTE and radiative transfer calculations even more complicated than in related objects, such as hot stars: The element abundances of type Ia supernovae are entirely dominated by heavy species that have fairly complicated ionic energy level structures with hundred-thousands of transitions. In addition, the high velocities within the ejecta broaden these lines by Doppler-shift and thus cause a strong overlap of sometimes thousands of lines especially in the UV wavelength regions. In contrast to objects with similar physical conditions (for example, hot stars or, in late phases, planetary nebulae), SNe are not illuminated by a central source of radiation, but are heated by the diffuse source of the γ-rays emitted by the radioactive decay of ^{56}Ni and ^{56}Co. Thus, the diffuse field is of primary importance and can not be approximated accurately in a simple way. Another problem concerns the relatively flat density distribution: Even for early phases where the assumption of an underlying photosphere seems to be justified, the radius of this photosphere (defined as the radius where the optical depth $\tau_\nu = 1$) varies strongly with wavelength.

The approach used in this project employs a detailed atmospheric model code which is based on the concept of *homogeneous, stationary, and spherically symmetric radiation-driven winds*, where the expansion of the atmosphere is due to scattering and absorption of Doppler-shifted metal lines. This code provides a detailed and consistent solution of the radiative transfer including a proper treatment of NLTE as well as blocking and blanketing effects in order to calculate realistic synthetic spectra (see [6], [5]). The computation of the NLTE level populations is carried out using detailed atomic models, and including all important contributions to the rate equations. Thomson scattering, bound-free and free-free opacities, line absorption and emission processes as well as dielectronic recombination is included in the radiative transfer. The computation of the NLTE model is based on several iteration cycles of step-wise improving accuracy. In a first step, an opacity sampling method is employed, which results in a approximate solution that is, however, already close to the final solution. An exact treatment of the radiative transfer equation in the observer's frame is performed in a second step. In a final step the occupation numbers, opacities and emissivities from the NLTE model are utilized for calculating a synthetic spectrum via a formal solution of the transfer equation. For a detailed description of the numerical methods we refer to [6].

1.4 Results

We regard the results obtained so far as not yet suitable for diagnostic purposes, since some physics relevant for SN modelling have been only very roughly included up to now (e.g., the heating by the diffuse source of the γ-rays emitted by the radioactive decay of ^{56}Ni and ^{56}Co). Thus, our present calculations should be considered as preliminary. All models obtained so far are based on the hydrodynamic model W7 by Nomoto et al. [4]. Since radial variation of the chemical composition has not yet been fully implemented in our models described here, the values used for the composition have been averaged over mass shells. Additionally we assume that the energy deposition arises completely from the optically thick part of the atmosphere. Moreover, the expansion of the ejecta is assumed to be homologous (i.e. $r \propto v$).

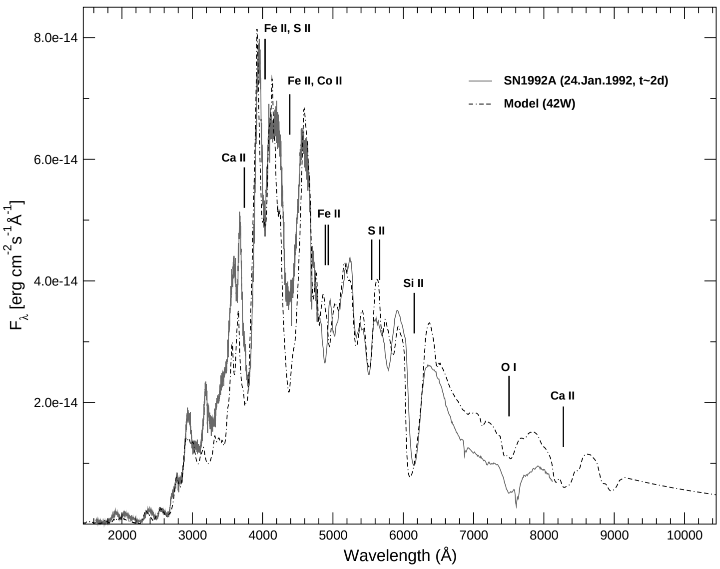

Figure 1: Model calculation compared to observed spectrum of SN1992A

Fig. 1 compares a calculated model spectrum to the observed "standard" type Ia supernova 1992A spectrum. As is shown, the synthetic spectrum reproduces the observed spectrum in the UV and blue wavelength ranges. Thus, our method already produces quantitatively reliable results indicating that the basic physics is obviously treated properly. However, towards the redder part of the spectrum a systematic offset to the observation appears. We regard our treatment of the inner boundary condition (diffusion approximation) and the missing energy deposition above the photosphere as a possible reason for this behavior. At the inner boundary we apply the diffusion approximation at all frequencies. This approximation is valid for conditions where the mean free path of the photons is very small (i.e. $\tau \gg 1$), which, however, is not guaranteed at longer wavelengths, due to the absence of strong lines in this wavelength range and the relatively flat density distribution that does not provide the required strong increase of the continuum opacities towards our innermost radius grid point. As a consequence, the flux emitted from the inner boundary is too high. In addition, the opacity in this wavelength range is dominated by pure electron (Thomson) scattering that does not couple the radiation field to the thermal pool. In these regions the radiation observed is actually generated in much deeper layers of the ejecta and scattered outwards.

1.5 Near future prospects

Regarding a solid basis for spectral diagnostics of type Ia supernovae the next steps are obvious. Depth-dependent abundances and a proper treatment of the γ energy deposition above the photosphere have to be included. The latter point will also free us from the limitation of currently being able to treat only the photospheric, early-phase epochs around maximum. With these enhancements it seems feasible to obtain synthetic spectra based on hydrodynamic explosion models like those of the hydrodynamics group at MPA, and to compare them directly to observed SN spectra.

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