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# Using Massively Parallel Processing of a NLTE Spectrum Synthetic Code and an Automated Comparison with Observations to Determine the Properties of Type Ia Supernovae from their Late Time Spectra.

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**Abstract.** The nebular spectra of SNeIa can be used to determine the mass, density, and distribution of the SN ejecta, and the distance and reddening to the SN. Synthetic spectra can very rapidly be computed in NLTE and compared to the observed ones. Given the relatively large number of parameters, it is convenient to explore the parameter space in an automated form. The nebular spectrum synthesis code can be run in parallel on a workstation cluster. Each synthetic spectrum is immediately compared to the observed one. Exploration of the parameter space can be guided by the information available on some quantities (e.g., line width). The results for a few cases of "normal" and possibly peculiar SNeIa are presented and discussed.

## 1. Introduction

In the nebular phase, the (emission) spectrum of a SN Ia is formed in the densest, innermost part of the ejecta, and is dominated by forbidden lines of Fe II and Fe III. Modeling this phase thus offers a unique opportunity to investigate the properties of the central region of the ejecta, where explosive nuclear burning is thought to be most efficient. Moreover, since nebular emission depends directly on the density, a successful model of this emission should yield values of the masses of the elements visible in the spectrum and, through the cooling effect of other elements, also of the total mass in the nebula. The parameter necessary to convert from density to mass is the velocity (the epoch is known), which can be inferred from the FWHM of the emission lines under the assumption of optically thin gas. Our model is based on a NLTE treatment of the rate equations for a nebula of uniform density. This simplifying assumption is reasonably well justified since all explosion models predict that the density near the centre of the ejecta is a much weaker function of radius than in the outer layers. The necessary input is then limited to the mass and composition of the ejecta, the sphere's outer velocity, and the time since explosion. Heating of the nebula comes from the deposition of energy generated in the radioactive $\beta$-decay of $^{56}$Co into $^{56}$Fe. This energy is produced in the form of $\gamma$-rays and positrons, which lose their energy in the ionization of the gas and in heating the plasma through collisions with electrons, in a cascade process. Eventually, a fraction of the produced energy is thermalized, and the heated gas cools by net emission of radiation. The electron density and temperature, as well as the population of the atomic levels and the emission line fluxes, are determined simultaneously from the conditions of statistical and thermal equilibrium.

The synthetic spectra are then corrected for the distance and reddening to the observed SN, and compared to the observed spectrum.

The basic treatment of nebular emission in a SN Ia was given by Axelrod (1980). A similar version of the code used here was employed by Ruiz-Lapuente & Lucy (1992), to which the reader is referred for further details. Our atomic data for the nebular spectrum model are from the sources quoted in Ruiz-Lapuente & Lucy (1992), with the exception of the [Fe II] collision strengths, which were obtained from Pradhan & Zhang (1993).

A further refinement included in this work is the introduction of the possibility that the gas is not distributed uniformly within the sphere. This is expressed in the form of a filling factor, which represents the fraction of the volume occupied by the gas. The effect of using a filling factor smaller than unity is to increase the local gas density, and thus to change the ionization regime.

In practice, the epoch and the velocity give the size of the sphere, while the mass and the filling factor give the density. The Ni mass gives the energy input. Since the epoch is known, and since we adopt a constant composition, apart from the decay of $^{56}$Ni into Co and Fe, there are three parameters that can be changed in the building of the physical model: velocity, mass, and filling factor. The remaining two parameters, distance and reddening, can be changed when comparing a synthetic model to an observed one. In this paper, we report on the modeling of a normal SN Ia: SN 1992A.

## 2. Implementation on a Parallel Computer Network

There are five unknown parameters: velocity $V$, mass $M$, filling factor $ff$, distance $\mu$, and reddening $E(B-V)$. We need to determine three of these to establish the SN proprietes. The grid can be set with a knowledge of the most likely range of properties for a normal SN Ia, while the distance and reddening grids are determined on the basis of observational estimates for the object under study, as show in Table 1.

Table 1. Range of values

| Parameters | Range | Step |
|---|---|---|
| $V$ | 6000–11000 | 500 |
| $M$ | 0.3–1.0 | 0.05 |
| $ff$ | 0.1–1.0 | 0.1 |
| $\mu$ | 30.0–33.0 | 0.25 |
| $E(B-V)$ | 0.0–0.2 | 0.02 |

We have a total 235,950 possible models. A single model on an high performance (57 MFLOPS) workstation such as an HP 735/125, takes 6 seconds, plus the time for the comparison with the observed spectrum. The simulation program can be split into two parts:

- **Physical model:** the spectrum at the source is created using the parameters ($M$, $V_b$, $ff$). This requires about 5 cpu seconds.
- **Synthetic spectrum:** the physical model is corrected for the observational parameters ($\mu$, $E(B-V)$). This requires about 1 cpu second.

Finally, a $\chi^2$ determination is used to check the goodness of the fit.

We used a very simple "master/slave" parallel architecture based on the LAM/MPI software:

**Master:** it first checks the available guest hosts, then it organizes the sharing of the tasks among the slaves. Every single task has a defined value for the parameter triplet ($M$, $V_b$, $ff$). When the entire parameter space has been scanned, the Master organizes all results into a single ASCII file containing the model parameters and the fitting test results.

**Slave:** it acquires the values of ($M$, $V_b$, $ff$), and creates the "physical spectra." It then uses an IDL procedure to convert from the "physical spectra" to the "synthetic spectrum," for values of $\mu$ and $E(B-V)$, which is compared to the observed spectrum. The results of the fit, which can be applied to the entire spectrum or to a particular region, are passed back to the Master.

Trieste Astronomical Observatory has a heterogeneous workstation environment, with 6 Sun and 14 HP computers available. For this work we used 9 homogeneous HP computers with a total power of 273 MFLOPS. The full computional work (i.e., simulation plus best fit test) was run at night at low priority and required about 16 hours, against the 493 hours which would have been required to run it sequentially.

## 3. Conclusions

In the case of SN 1992A, the velocity was first determined as $v = 8500\,\mathrm{km\,s^{-1}}$ from fitting the line width. Since the (small) reddening is known, ($E(B-V) = 0.02$), good fits can be obtained for different values of the mass and the distance, if different values of the filling factor are used.

The interesting result is that the best fits for the various values of $ff$ are practically indistinguishable, as shown in Figure 1. Some physical insight must therefore be applied. If we assume that we know from explosion models the mass ejected with velocities below the observed value, then an estimate of the most likely values of distance and filling factor can be derived (Figure 2).

In the standard SNIa explosion model (W7, Nomoto et al. 1984), 1.4 $\mathrm{M}_\odot$ of material is ejected, 0.7 $\mathrm{M}_\odot$ of which has velocities below 8,500 $\mathrm{km\,s^{-1}}$. The best fitting model for this value of enclosed mass has $\mu$ ~31.5 mag and $ff$ ~0.55.

Using the tools available at the Observatory (IDL and a distributed password system), and a public domain software package (LAM/MPI Parallel Computing), it is possible to create, optimize, and automate the comparison of synthetic spectra with observed Supernova spectra. The scientific user must then decide (as pointed out above) the correct physical properties if best fits having similar appearance, but different physical characteristics, are present.

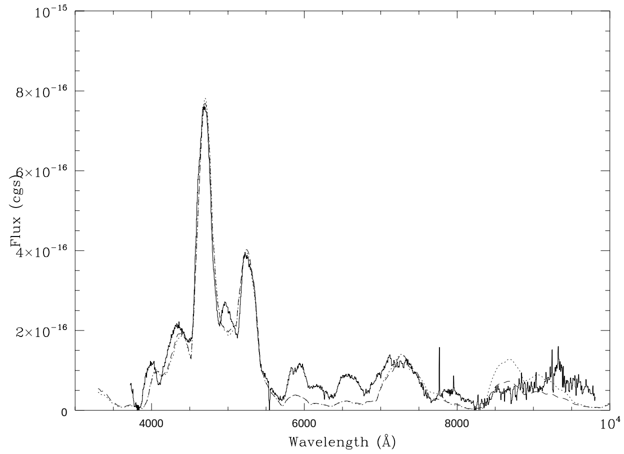


Figure 1. The spectrum of SN 1992A (continous line) compared to the best fitting models for $ff = 0.5$ (dotted line) and $ff = 1.0$ (dash-dotted line). The corresponding values of mass and distance can be read from Figure 2.

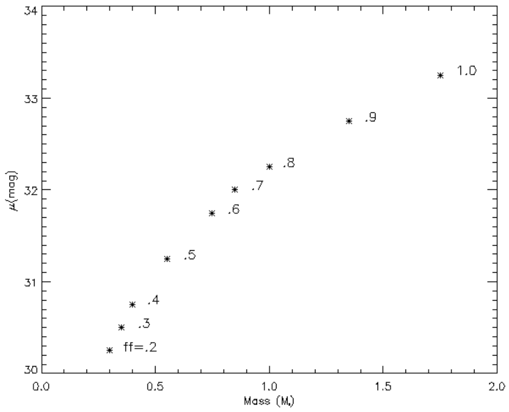


Figure 2. Best fit for various filling factors.

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