ANALYSIS OF THE TYPE IA SUPERNOVA SN1994D

P. HÖFLICH
Harvard University, Center for Astrophysics
60 Garden Str., Cambridge, MA 02138, USA

1. Introduction

On Mar. 7, 1994, Treffers, Filippenko and Van Dyk (1994) discovered the Type Ia supernova (SN Ia) 1994D in the SO galaxy NGC 4526, a member of the Virgo cluster which was about 12 days before maximum light. Subsequently, both the light curve in Johnson’s UBVRI colors and spectra a have been monitored by several groups (e.g. Filippenko et al. private communication, Smith et al., 1995) making this supernova one of the best observed until now. In addition, starting at Mar 12, IR-spectra are reported to be taken at the Royal Greenwich Observatory showing a P-Cygni line at about 1.0 $\mu$m which, likely, is due to He I (Meikle 1995).

It is generally accepted that SN Ia are thermonuclear explosions of carbon-oxygen white dwarfs (WD) (Hoyle & Fowler 1960). However, details of the scenario are still under debate. For discussions of various theoretical aspects see e.g. Wheeler & Harkness 1990, Canal 1995, Nomoto et al. 1995, Höflich & Khokhlov 1995, Woosley & Weaver 1995). What we observe as a supernova event is not the explosion itself but the light emitted from a rapidly expanding envelope produced by the stellar explosion. As the photosphere recedes, deeper layers of the ejecta become visible. A detailed analysis of the light curves (LC) and spectra gives us the opportunity to determine the density, velocity and composition structure of the ejecta.

2. Comparison of light curves and spectra

Our analysis is based on observations of SN1994D by the supernova group at the Center for Astrophysics. For the first time, a detailed analysis of a Type Ia supernova is presented which is consistent both with respect to the explosion mechanism, the optical and infrared light curves, and the spectral evolution. The only free parameters are the initial structure of the WD and
Figure 1. Observed V and B LCs for SN1994D in comparison to the theoretical LCs of the deflagration W7, the delayed detonation N21, the helium detonation HeD10, the pulsating delayed detonation PDD3, and the envelope model DET2env4.

The explosions are calculated using one-dimensional Lagrangian hydro with artificial viscosity (Khokhlov, 1991) and radiation-hydro codes (Höflich & Khokhlov 1995) including a nuclear network. Subsequently, the LC are constructed. Spectra are computed for several instants of time using the density, chemical, and luminosity structure resulting from the light curve code which includes the solution of the radiation transport implicitly via the moment equations, expansion opacities, a detailed Monte-Carlo $\gamma$-ray transport, and a detailed equation of state. Our NLTE code for calculating synthetic spectra solves the relativistic radiation transport equations in comoving frame consistently with the statistical equations and ionization due to $\gamma$ radiation for the most important elements (He, C, O, Ne, Na, Mg, Si, S, Ca, Fe). About 300,000 additional lines are included assuming LTE-level populations and an equivalent-two-level approach for the source functions. For more details on technical aspects and a discussion of the relation between observational properties and the underlying model, see Khokhlov et al. (1993), Höflich (1995), Höflich & Khokhlov (1995), Höflich et al. (1995, this volume) and references therein.

Although not presented in detail for all models available (see Nomoto et al., 1984, Khokhlov et al. 1993, Höflich et al. 1994, Höflich, 1995, Höflich & Khokhlov, 1995), we have compared the observed optical and infrared light curves of SN1994D for deflagration (W7, DF1), pulsating delayed detonation (PDD1a-c,3-9), delayed detonation (N21, N32, M35-39), helium detonations (HeD2-12), and envelope models (DET2env2-4) being a crude representation of a merger scenario.

The pulsating delayed detonation models, helium detonation and envelope models can be ruled out because of the shape of their V and B light
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Figure 2. Some Abundances as a function of the expansion velocity for the delayed detonation model M36.

Figure 3. Observed LCs of SN1994D in comparison to the theoretical LCs of M36.

curves (Fig.1). W7 and N32 that fit observations of several SNe Ia (Müller & Höflich, 1994) provide better fits to SN1994D, but they fail to reproduce the IR light curves (Höflich 1995) and, less critical, the post-maximum decline in V. One may conclude that SN1994D is no 'standard' Type Ia supernova, but it is close to standard. We find best agreement between theory and observation for a the delayed detonation model M36 with $\rho_{tr} = 2.4 \times 10^7 \text{g/cm}^3$ and a deflagration velocity of 0.03 times the sound velocity (Figs. 2 & 3). The initial central density of the WD is $2.7 \times 10^9 \text{g/cm}^3$, i.e. about 20% lower than in our delayed detonation models previously considered. The lower density may be understood in terms of a higher accretion rate on the progenitor. During the explosion, 0.6$M_{\odot}$ of $^{56}\text{Ni}$ are produced. Similar
models with $\rho_{tr}$ of $2.0 \times 10^7$ and $3.0 \times 10^7 g/cm^3$ and Ni productions of 0.51 and 0.67 $M_\odot$, respectively, are not able to reproduce the observations.

From the vertical shift of the light curves, the time of explosion can be determined to be between JD 244 9414.5 and 244 9415.5, meaning SN1994D was discovered just about 3 to 4 days after the explosion! Our models are consistent with no interstellar reddening. Taking the uncertainties in our models into account, we determine the distance of NGC 4526 to be $16 \pm 2$ Mpc. The explosion took place between March 3rd and 4th, 1994.

The NLTE-analysis of the spectra confirmed the results from the LC analysis and give an insight to several new aspects. Taking into account that we do not allow for any artificial adjustment to provide better fits, M36 reproduces the observed spectra reasonably well (Höflich, 1995). The agreement of the velocity shifts both of the elements of partial burning such as Si, S, O and also the iron rich elements indicate that the chemical and density profiles of M36 seem to resemble SN1994D. In the spectrum from March 11, the Doppler shift of the absorption minimum of Si II indicates photospheric expansion velocities of $\approx 15000 km/sec$ with wings reaching out to more than $22000 km/sec$. This strongly suggest the presence of a significant amount of Si at high velocities. Our delayed detonation model M36 provide a Si mass fraction of 15 % up to the outer layers ($\approx 25000 km/sec$, Fig. 1). For comparison, the classical deflagration model W7 does not show Si at velocities...
≤ 16400 km/sec because the smaller flame speed in the outer layers and, consequently, the larger pre-expansion of the WD envelope during the explosion. In our previous analysis, we had to report the serious problem that the Ti features are too strong and, artificially, we had to reduce Ti in the outer layers. In recent calculations for delayed detonation models (Höflich et al. 1995), we find that the Ti problem vanishes if we use a larger nuclear network and start with a metallicity according to a population II star.

Finally, we want to mention some of the limitations of our study. Despite similarities in both the spectra and light curves, the photospheric expansion velocities inferred from observed spectra show strong individual variations (e.g. Branch 1987 and Barbon et al. 1990). Different models are needed to fit the light curves (Müller & Höflich 1994, Höflich et al. 1994). Therefore, the results of our study must not be generalized. Although we treat several elements in full NLTE, detailed atomic models shall be implemented for the iron group elements, namely Ti, Co, Ni. Our approach to the line scattering by using an equivalent level approach for the ‘LTE-lines’ seems to work, but it must be regarded only as a first step towards a more consistent treatment. Finally, M36 produces only 0.003 $M_\odot$ of He in the region of α rich freeze-out whereas, a much larger amount is needed to produce a strong He feature at 1.$\mu$. For a more detailed discussion of the latter problem, see Meikle 1995.

3. References

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