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CONSTRAINING TYPE IA SUPERNOVA MODELS WITH SNLS SPECTRA

F. Cellier-Holzem[1] and C. Balland[1]

Abstract. The use of type Ia supernovae for cosmology is limited today by systematic uncertainties. To reduce these uncertainties and standardize these objects, we have to better understand their physical properties. For this purpose, we compare type Ia supernova spectra from the SuperNova Legacy Survey with the predictions of two supernova explosion models (a deflagration and a delayed detonation models) in order to constrain and improve them.

Keywords: type Ia supernova, cosmology, SuperNova Legacy Survey, supernova formation models

1 Cosmological context and aim

The use of type Ia supernovae (SNeIa) allows to constrain the accelerated expansion of the universe via the cosmological parameters (Riess et al. 1998; Perlmutter et al. 1999). Using the first three year data set of the Supernova Legacy Survey (SNLS), supplemented with nearby, intermediate and high redshift supernovae, Conley et al. (2011) obtain $w = -0.91^{+0.16}_{-0.20}(stat)^{+0.07}_{-0.14}(sys)$ assuming a flat universe. A better knowledge of of type Ia supernova properties will permit to reduce the systematic uncertainties in the future. Supernova formation models producing spectra and light-curves, will help us to understand the SNeIa. In the present study, we compare SNLS spectra with synthetic spectra produced by a pure deflagration model (W7) and a delayed detonation model (DD25) (Nomoto et al. 1984; Khokhlov 1991; Hoeflich et al. 2002). We evaluate how observations can discriminate models, in order to constrain and improve them.

2 Explosion models : W7 and DD25

We use two synthetic spectra samples : one combined W7 with the radiative transfer code *Phoenix*, the other combined DD25 (with $\rho_{tr} = 25.10^6 g.cm^{-3}$, the transition density between the deflagration and the detonation) with the same radiative transfer code *. These spectra are produced from 5 to 50 days since the beginning of the explosion for W7 and from 7 to 50 days for DD25, with a regular sampling near the maximum light. Both models describe the explosion of a carbon and oxygen white dwarf reaching Chandrasekhar mass limit : a nuclear explosion producing intermediate and iron peak elements. The burning front is a key parameter governing the final element composition as predicted by the models. A different burning front velocity implies differences between the two models. These differences are shown in Fig. 1 where we overlap a DD25 and a W7 spectrum at maximum light ($\sim$ 18 days).
The differences are more pronounced in the UV part of the spectra ($\lambda < 4300$Å), in particular for the absorption depth of calcium II at $\lambda \sim 3700$Å and the peak amplitude at $\lambda \sim 4150$Å. In the same spirit, differences are noticed with two peaks at $\lambda \sim 3200$Å and $\lambda \sim 2900$Å. The spectrum produced by W7 is more structured than the DD25 spectrum : spectral structures are missing in the DD25 spectrum (peaks in W7 spectrum at $\lambda \sim 3400$Å and $\lambda \sim 3650$Å). Clearly, the UV spectral zone will be discriminant for the models.

[1] Laboratoire de Physique Nucléaire et Hautes Énergies (LPNHE), Paris, France
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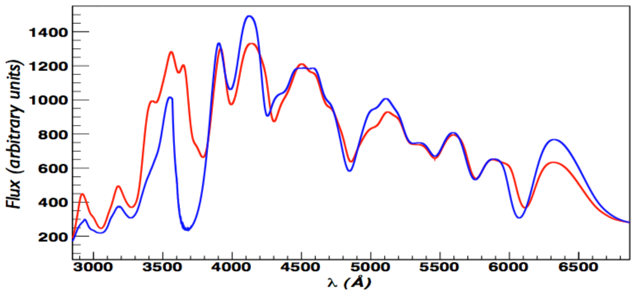

Fig. 1. Overlap of 18 days W7 (red line) and 18 days DD25 (blue line) spectra showing the spectral differences between the models.

3 SNLS spectra

The SNLS is a 5 year experiment aiming at measuring the luminosity distance of a large number of intermediate and high redshift SNeIa in order to constrain cosmological parameters (Astier et al. 2006; Sullivan et al. 2006; Guy et al. 2010). Conducted from 2003 to 2008, this experiment is split in two surveys :

- an imaging survey with the Canada-France-Hawaii Telescope (CFHT) in Hawaii, to detect the supernovae and monitor their light-curves in several photometric bands,

- a spectroscopic program with the Very Large Telescope (VLT), Gemini and Keck telescopes to confirm the nature of the SNeIa candidates and measure their redshift.

SNLS measured 242 SNeIa during the first three years of operation. For the present study, we use an homogenous subset of 51 SNeIa spectra measured at the VLT for which a separate extraction of the supernova and the host galaxy is possible to limit the host contamination (Balland et al. 2009). This spectra are measured in a large range of redshift ($0.15 < z < 1.0$) with a regular phase distribution ($-8d < phase < 13d$) where the phase is the number of rest-frame days elapsed since the B-band maximum date.

4 Observations vs Models

4.1 *Fitting SNLS spectra with synthetic spectra*

In this section, we compare SNLS spectra with the models. We perform a χ^2 minimization fit of each SNLS spectrum by the two synthetic spectra samples (W7 and DD25). We do the fit at each W7 and DD25 spectrum phase. In some cases, W7 is the best fit, as shown in Fig. 2 for SN 04D2cf, a supernova at $z = 0.368$ with a phase of 8.48 days. This is clearly visible in the UV part, where the Ca II absorption line ($\lambda \sim 3700$Å) and the amplitudes of the peaks around the silicon II feature ($\lambda \sim 4000$Å) are well reproduced by W7 (on the left panel of Fig. 2) and not by DD25 (on the right panel of Fig. 2).

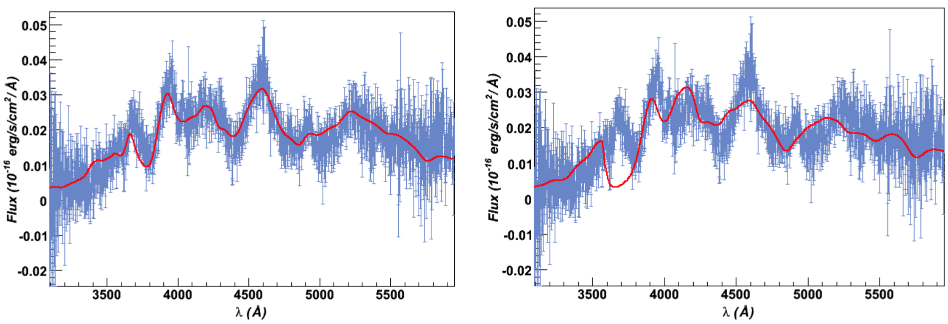

Fig. 2. SN 04D2cf (blue) at z=0.368 with phase=8.48 days, fitted by the models (red). **Left:** 24 days W7 spectrum (best fit) **Right:** 20 days DD25 spectrum.

On the contrary, for some supernovae, DD25 is favoured by the data, as shown in Fig. 3 for SN 04D2an, a supernova at $z = 0.362$ with a phase of -3.39 days. Again, the UV part is the discriminant zone of the spectrum.

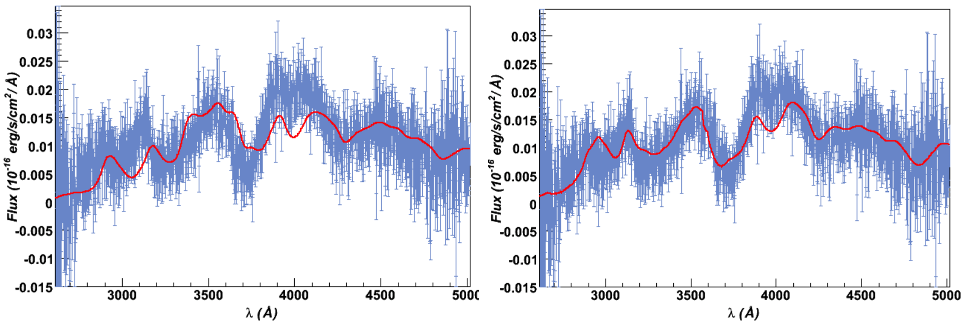

Fig. 3. SN 04D2an (blue) at z=0.362 with phase=-3.39 days, fitted by the models (red). **Left:** 16 days W7 spectrum **Right:** 14 days DD25 spectrum (best fit).

4.2 Do the data really discriminate the models ?

We test the null hypothesis that the models reproduce equivalently well the data. For this purpose, we perform a F-Test : for each fit, we compute the χ^2 ratio $F = \chi_1^2/\chi_2^2$ where 1 is the model with the smaller χ^2 (W7 or DD25). This F quantity follows a Fisher probability law. If the F probability $P(F) \simeq 1$, the hypothesis is true and the data cannot discriminate the models. On the contrary if $P(F) \ll 1$, the hypothesis is false and one of these two models is favoured (model with the smallest χ^2). We consider that observations can discriminate models when the probability is smaller than 5% (choosing another cut do not change the results). Among the 51 observed spectra, 21 pass this cut. We end up with two subsamples : one for the W7 best fit spectra, and the other for DD25.

We now investigate if these subsamples represent different populations of type Ia supernovae. For this purpose, we compare the average photometric properties of these two subsamples (Table 1).

	$\langle M_B \rangle$	$\langle s \rangle$	$\langle c \rangle$	host type
W7 (13 spectra)	-19.20 ± 0.04	1.014 ± 0.024	-0.021 ± 0.018	50% early-type - 50% spiral
DD25 (8 spectra)	-19.30 ± 0.04	1.048 ± 0.022	0.003 ± 0.021	17% early-type - 83% spiral

Table 1. Average photometric properties of the two subsamples best fitted by W7 or DD25 (errors are errors on the mean).

First, we compare the average absolute magnitude $\langle M_B \rangle$ of the two subsamples (column 2 of Table 1). We find that DD25 fits better brighter SNeIa (with a smaller M_B, $\langle M_B \rangle = -19.30 \pm 0.04$) than W7 ($\langle M_B \rangle = -19.20 \pm 0.04$).

Column 3 of Table 1 shows the average stretch $\langle s \rangle$ (stretch is a light-curve shape parameter). SNeIa best fitted by DD25 have a marginally higher stretch ($\langle s \rangle = 1.048 \pm 0.022$) than SNeIa best fitted by W7 ($\langle s \rangle = 1.014 \pm 0.024$). This is consistent with the well known *brighter-slower* empirical correlation observed for SNeIa.

Another empirical correlation, called *brighter-bluer*, exists for SNeIa between the luminosity and the color c. Column 4 of Table 1 shows that there is not significant difference between the color of the W7 ($\langle c \rangle = -0.021 \pm 0.018$) and the DD25 subsample ($\langle c \rangle = 0.003 \pm 0.021$).

Finally, column 5 of Table 1 shows a correlation between the SNeIa and the host galaxy : brighter supernovae are preferentially in spiral galaxy and fainter SNeIa in early type galaxy (elliptic). It seems that DD25 reproduces this tendency (83% in an spiral galaxy) but it is less visible for W7 (50% in an early type galaxy).

To summarize, W7 fits better on average fainter supernovae with a smaller stretch and DD25, brighter supernovae in spiral galaxy with an higher stretch. We do not find color difference between the subsamples best fitted by W7 and DD25.

4.3 Why is a model favoured by the data ?

As stated earlier, a large of W7 and DD25 spectral differences can be attributed to the Ca II feature ($\lambda \sim 3700$Å). We compute the equivalent width of Ca II (EW Ca) for synthetic spectra. The time evolution of EW Ca is shown on the left panel of Fig. 4. Notice that EW Ca for DD25 is twice as big as for W7 : the Ca II absorption line predicted by DD25 is deeper than for W7. The right panel of Fig. 4 shows the EW Ca computed for the observed spectra best fitted by W7 (red points) and for spectra best fitted by DD25 (blue points) for phases from -5 days to 12 days. DD25 is clearly favoured by earlier phases spectra because the EW Ca for W7 spectra is too small compared to the data. For post maximum phases, the EW Ca for DD25 spectra is too big compared to the data and W7 is thus favoured.

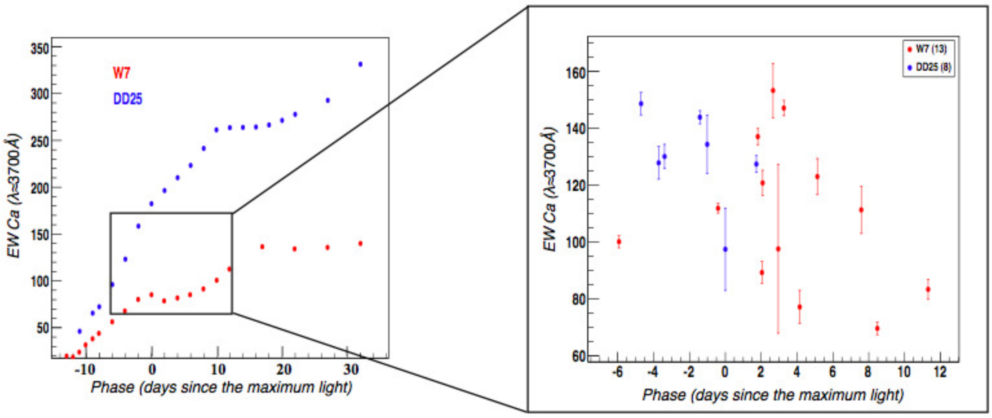

Fig. 4. Time evolution of EW Ca **Left:** for W7 (red) and DD25 (blue) model spectra **Right:** Same as left for the two observed spectra subsamples best fitted by W7 (red) and DD25 (blue). The ranges of EW Ca values and phases match those shown in the box on the left panel.

5 Conclusions

We have shown that SNLS spectral data have the power to discriminate some models. Better quality spectra from the SuperNova Factory (SNFactory) will allow us to confirm this result in the near future. We also plan to use a larger set of models to broaden the physical parameter space describing SNeIa. Our goal is to improve these models, reproduce the differences between SNeIa and understand their physical properties for a better calibration of SNeIa for cosmological use.

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