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The chemical composition of the ejecta of the rare type IIb supernova 2013df

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SN 2013df, appeared in the nearby galaxy NGC 4414 at a distance of ∼17 Mpc, is a type IIb supernova. Members of this subclass are intermediate between the hydrogen-rich type II-P SNe and the hydrogen-poor, stripped envelope Type Ib/c explosions. Their progenitors are thought to be massive (∼20 $M_{\odot}$) stars, which may have interacting binary companions. Up to now, detailed analyses have been published on only a few type IIb SNe observed from the very early phases. Thus, it is important to study well-observed individual objects as thoroughly as possible.

Our team collected a sample of high-quality data on SN 2013df. Here we present the results of our spectroscopic analysis based on 6 optical spectra obtained between June 13 and July 8, 2013 with the 9.2m Hobby-Eberly Telescope (HET) Marcario Low Resolution Spectrograph (LRS) at McDonald Observatory, Texas. We applied the SYN++/SYNAPPS spectral synthesis codes to get information on the chemical composition and physical properties of the ejecta. The spectral evolution, based on the comparison with other type IIb SNe 1993J and 2011dh, is also presented and discussed.

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1. Introduction

Type IIb SNe are thought to arise from the core-collapse of massive ($M > 8\ M_{\odot}$) stars that lost most, but not all, of their thick H envelopes prior to explosion. This explains the unique spectral evolution characteristic of the IIb subtype, like strong Balmer features around maximum light and strong He features after maximum light. Based on some theoretical and observational results, the progenitors of such explosions may be members of interacting binary systems. Up to now, detailed analyses have been published on about a dozen of type IIb SNe; the most famous examples of this type are SN 1993J [1, 2] and SN 2011dh [3-5].

Here we present the spectroscopic analysis of the nearby (D = 16.6 ± 0.4 Mpc) [6, 7] type IIb SN 2013df. This object, located 32″ east and 14″ south from the center of the spiral galaxy NGC 4414, was discovered on June 8, 2013 [8]. The first spectrum, obtained by Cenko et al. [9], showed clear resemblance to the early spectra of SN 1993J, which suggested that SN 2013df is a type IIb supernova. This statement was verified by Van Dyk et al. [7], who presented some early photometric and spectroscopic data, and also made assumptions to the properties of the progenitor. Morales-Garoffolo et al. [10] also analyzed the early UV-optical light curves and some spectra (including nebular ones), and concluded that the progenitor was a compact star with an extended H envelope.

While [7] and [10] contain many interesting results concerning to SN 2013df, the detailed spectroscopic analysis of the object has not been published up to now. In the following sections we present our data and the results based on modeling of well-sampled spectra over the first month after explosion.

2. Observations

Our team collected a sample of high-quality spectroscopic data on SN 2013df. The object was monitored with the Marcario Low Resolution Spectrograph (LRS) on the 9.2m Hobby-Eberly Telescope (HET) at McDonald Observatory, Texas. The left panel of Fig. 1 shows all the 6 spectra (R = 300) taken between June 13 and July 8, 2013, during the first month after explosion. The comparison of the spectra of SN 2013df with spectra of SNe 1993J and 2011dh is shown in the right panel.

3. Spectral modeling

We applied the parametric codes SYN++ and SYNAPPS [12] to model the spectroscopic evolution of SN 2013df. SYN++/SYNAPPS is based on the following assumptions:

- spherically symmetric, homologously expanding ejecta: $v(r) = v_{max} \cdot r/R_{max}$;
- high velocity gradient in the ejecta (Sobolev approximation);
- sharp photosphere, radiating as a blackbody with temperature T_{bb};
- pure scattering line formation above the photosphere;

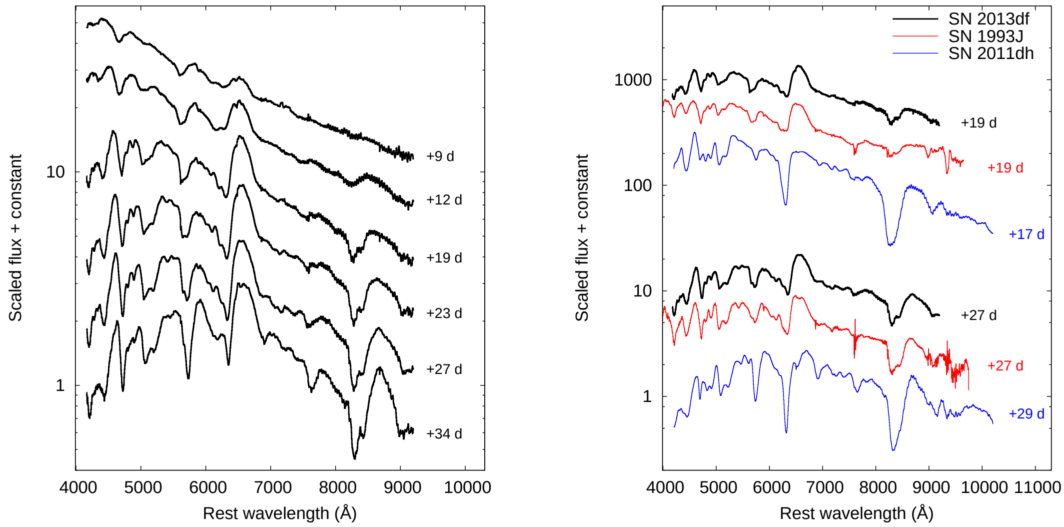

Figure 1: *Left:* Observed HET spectra of SN 2013df. Phases are given relative to the explosion date (t_0 = 2,456,447.8 ± 0.5 JD, or June 4.3 UT) determined by Van Dyk et al. [7]. *Right:* Spectra of SN 2013df compared with spectra of other type IIb SNe 1993J [11] and 2011dh [5] at similar ages.

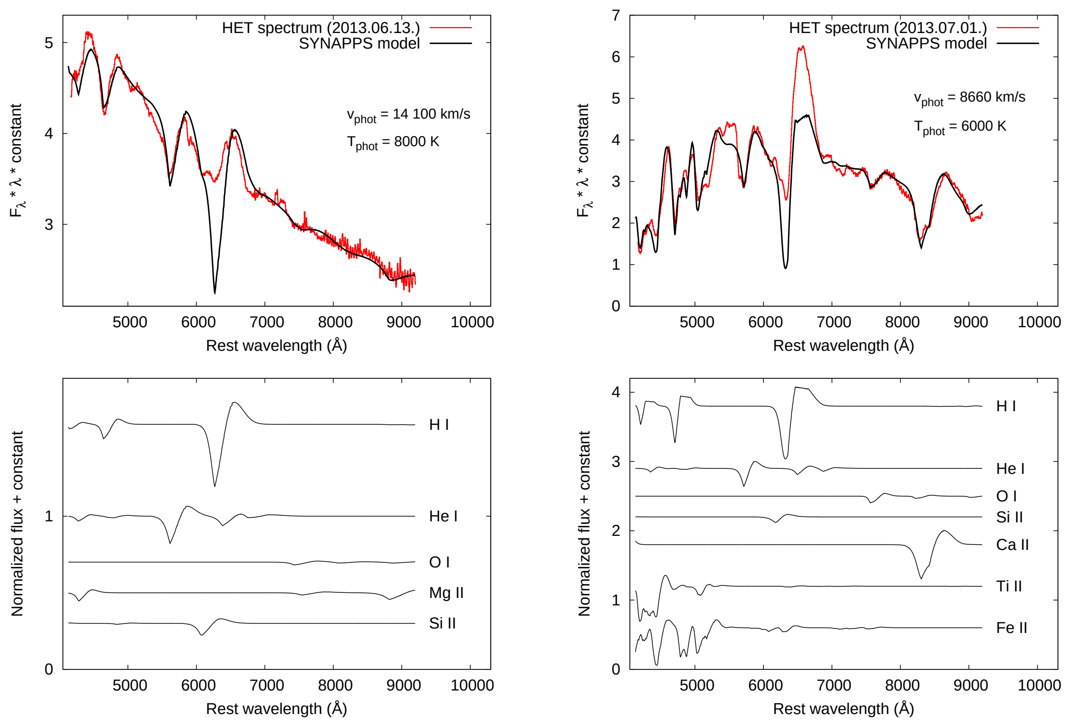

Figure 2: Best-fit SYNAPPS models of two selected spectra (+9 and +27 days), and the contribution of the most abundant elements to the model spectra.

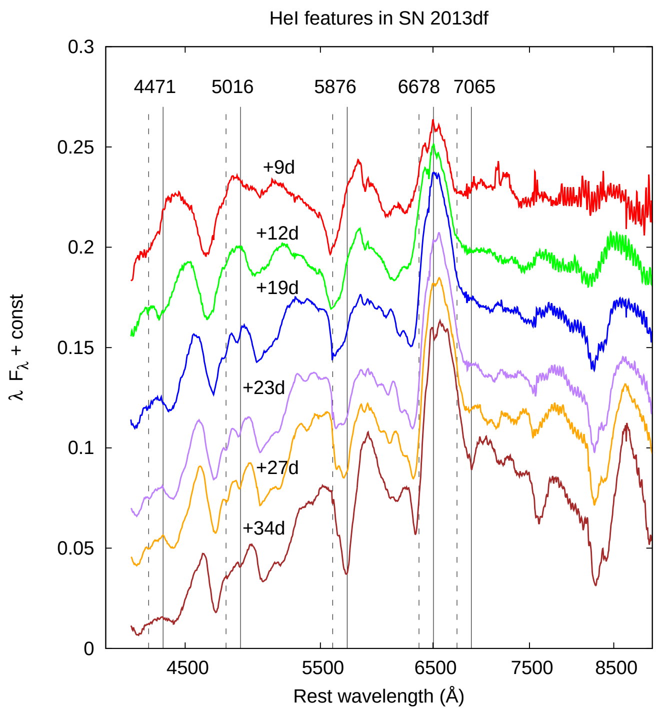

Figure 3: Spectral evolution of SN 2013df (from top to bottom). Solid and dashed vertical lines mark the positions of low- and high-velocity He I features, respectively.

- line strengths are specified by the optical depth of the strongest feature of a given ion;
- relative line strengths are set by the Boltzmann formula (i.e. LTE).

Before the fitting all spectra were corrected for Galactic and host extinction ($A_V = 0.3$ mag) [7] and the redshift of the host galaxy using $z = 0.0024$ [13]. Best-fit SYNAPPS models of two selected spectra (+9 and +27 days), and the contribution of the most abundant elements to the model spectra are shown in Fig. 2.

It can be seen that models fit well the whole spectra except the H_α profile. Our explanation is that, in this case, resonant scattering is the dominant process over absorption. The flat-top of the H_α profile in the +27d spectrum was modeled by assuming the H-layer detached from the photosphere by $\sim$ 1000 km s^{-1}.

4. High-velocity He I features

We found signs of high-velocity (HV) He I features in the early spectra. At +9d and +12d the He I λ5876 profile can be fit with HV He I at $v \sim 14,000$ km/s. A lower velocity component at $v \sim 7,800$ km/s appears after +19d. Similar but less conspicuous HV features are also seen in the He I λ5016, λ6678, and λ7065 lines. Similar line profiles are found in the spectra of SN 1993J [2, 11].

Early HV features might form in the low-mass H-rich envelope on top of the denser, He-rich core. The evolution of the He lines can be described with the inward motion of the photosphere from the high-velocity outer envelope to the more slowly expanding core.

5. Results and conclusions

As it is seen in the right panel of Fig. 1, SN 2013df shows high similarity to the spectroscopic evolution of the prototype SN 1993J [2, 11]. At the same time, spectra of SN 2011dh [5] are quite different, which shows that type IIb SNe do not form a homogeneous group.

The main conclusions from our spectral analysis (see Figs. 2 and 3):

- strong Balmer features are persistent during the first month suggesting a hydrogen-rich outer envelope;
- He I features, detected even in the earliest spectrum at +9d, are getting stronger, unlike in 'normal' type II-P SNe – this is the main characteristic of type IIb SNe;
- we found signs of HV He I features in the early spectra, while lower velocity component appears only after +19d.

As the bottom panels of Fig. 2 show, H I, He I, Si II, and Mg II are the most abundant elements in the ejecta in the earliest phase, while Ca II, Fe II, and Ti II features become strong after +19d (which is around the epoch of the optical photometric maximum).

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