High-Resolution Optical Studies of Nearby Type Ia Supernovae

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Summary. Since April 2000, a program using the ESO/VLT/UVES[6] to search for early circumstellar signatures from nearby supernovae has been conducted.[7] Until now, two Type Ia supernovae have been observed, SNe 2000cx and 2001el. Here we report on preliminary results for SNe 2001el, and we discuss how the observations can be used together with detailed modeling to derive an upper limit on the putative wind from the progenitor system. For a hydrogen-rich wind with velocity 10 km s^{-1}, the mass loss rate for the progenitor system of SN 2001el is $\dot{M} \lesssim 1 \times 10^{-5}$ M$_\odot$ yr^{-1}.

1 Introduction

The origin of Type Ia supernovae (SNe Ia) is still unclear. Branch et al. [3] list possible types of systems, and argue that the most likely system is a C-O white dwarf which accretes matter from the companion, either through Roche lobe overflow, or as a merger with another C-O white dwarf. We need methods to discriminate between the possible progenitor scenarios. In non-merging scenarios a wind from the companion star is expected. If the wind is ionized and dense enough, it could reveal itself in the form of narrow lines before being overtaken by the supernova blast wave, just as in narrow-line core-collapse supernovae, SNe IIn. For a hydrogen-rich wind, Hα would be

[6] Based on observations collected at the European Southern Observatory, Paranal, Chile. Program ID 67.D-0227(A).
[7] See http://www.astro.su.se/∼peter/sntoo.html. In collaboration with the SN Ia RTN team (PI: W. Hillebrandt), see http://www.mpa-garching.mpg.de/∼rtn

emitted, and if helium dominates He I $\lambda\lambda$5876, 10830 and He II λ4686 may be prominent.

A pioneering observational and theoretical study of circumstellar line emission in SNe Ia was that of SN 1994D [6, 10]. The spectrum was obtained ~ 6.5 days after explosion with a spectral resolution of ~ 30 km s^{-1}, and covered Hα. The analysis of the non-detection involved full time-dependent photoionization calculations to estimate the narrow Hα emission from the tentative wind. The analysis in [10] gave an upper limit on the mass loss from the progenitor system of $\dot{M} \lesssim 2.5 \times 10^{-5}$ M$_\odot$ yr^{-1}, assuming cosmic abundances for the wind, and a wind speed of $v_w = 10$ km s^{-1}. More recently, Lundqvist et al. [12] studied SN 2000cx with the Ultraviolet and Visual Echelle Spectrograph (UVES) on ESO's Very Large Telescope (VLT). The spectral resolution of UVES is $\approx 50,000$, i.e., 6 km s^{-1} in the region of Na I D and Hα. The preliminary upper limit on the mass loss rate from the progenitor system is $\dot{M} \lesssim 9 \times 10^{-6}$ M$_\odot$ yr^{-1} for $v_w = 10$ km s^{-1}. Here we report on the second of our SNe Ia observed with VLT/UVES, SN 2001el.

2 Observations and Results

SN 2001el was discovered on September 17.1 2001 [13]. It was situated 9" west and 15" north of the nucleus of the nearby (recession velocity v$_{rec} = 1164$ km s^{-1}) galaxy NGC 1448. SN 2001el was observed as part of our VLT/UVES Target-of-Opportunity (ToO) program on September 21. This spectrum had a complete wavelength coverage between $3260 - 10600$ Å and allowed a classification of the supernova as a Type Ia observed well before maximum [15]. SN 2001el was also observed on September 26, and then revisited for the last time on September 28. Our UVES observations were thus obtained 9, 4 and 2 days before the supernova B-band maximum light [8].

The lines expected from a hydrogen- or helium-rich companion wind were sought for in the SN spectra at the three epochs of observation at the expected range of wavelengths assuming $v_{rec} = (1180 \pm 300)$ km s^{-1} for the supernova. No such lines were detected, and therefore upper limits for the emission line fluxes and absorption line equivalent widths were derived. This was done by fitting Gaussian profiles with fixed FWHMs at fixed positions within the expected range of wavelengths in the unbinned spectra. The 1σ levels for the emission line fluxes and absorption line equivalent widths were then obtained by requiring 68.3 % of the measured line fluxes (or equivalent widths) to be below this level. Adopting an extinction of A$_V = 0.83$, a distance of $d = 18$ Mpc for SN 2001el and assuming that the line has a FWHM of 10 km s^{-1}(see Mattila et al. in prep.), we obtain an upper limit for the Hα narrow line-luminosity of $L_{\mathrm{H}\alpha} = 3.2 \times 10^{36}$ ergs s^{-1} in our third epoch (Sep 28.3 UT) spectrum. To reach this limit, we performed a careful background subtraction of the host galaxy emission. This was done manually outside the UVES pipeline.

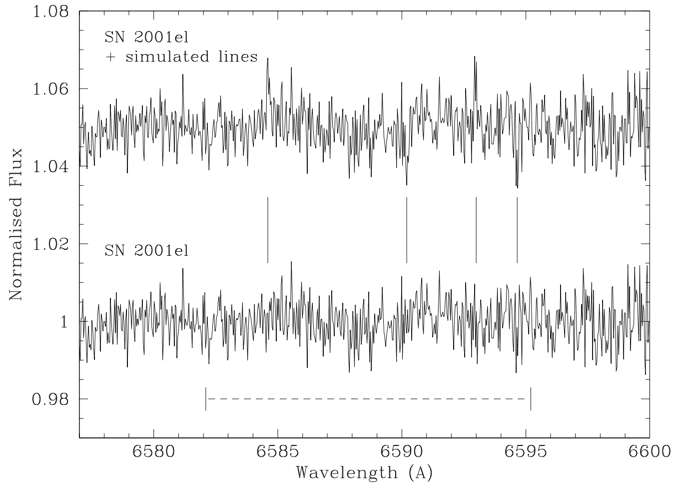

Fig. 1. Normalized third epoch (Sep 28.3 UT) spectrum of SN 2001el showing the region around the expected wavelength range of Hα (marked with a horizontal dashed line). The lower and uppermost plots, respectively, show the SN spectrum before and after including simulated 3σ features with a Gaussian profile and FWHM of 6 km s^{-1}. The locations of these features at 6584.6 Å (emission), 6590.2 Å (absorption), 6593.0 Å (emission), and 6594.7 Å (absorption) are marked with vertical lines. The spectra have been rebinned by a factor of 2, and thus have a pixel size of $\sim$1.6 km s^{-1}. The uppermost spectrum has been moved upward for clarity.

Figure 1 shows examples of artificially introduced unresolved emission and absorption lines at the 3σ level. These lines with FWHM = 6 km s^{-1} were simulated at the expected wavelength range of Hα in the unbinned third epoch UVES spectrum. The spectrum was then rebinned by a factor of 2 resulting in a pixel size of $\sim\frac{1}{4}\times$ FWHM in the rebinned spectrum. The simulation parameter for the line peak was selected for each line such that the measured apparent flux of the line corresponds to the 3σ level. No features with fluxes (or equivalent widths for the absorption lines) as high as the ones of the simulated lines are apparent in the real data.

3 Modeling and Discussion

We have modeled the line emission in a way similar to what was done in [6, 10, 12]. We assume that the supernova ejecta have a density profile of $\rho_{ej} \propto r^{-7}$, and that the ejecta interact with the wind of a binary companion which has a density profile of $\rho_w \propto r^{-2}$. The power-law density distributions makes it possible to use similarity solutions for the expansion and structure of the interaction region [4]. Calculations are started at $t_0 = 1.0$ day, and at this

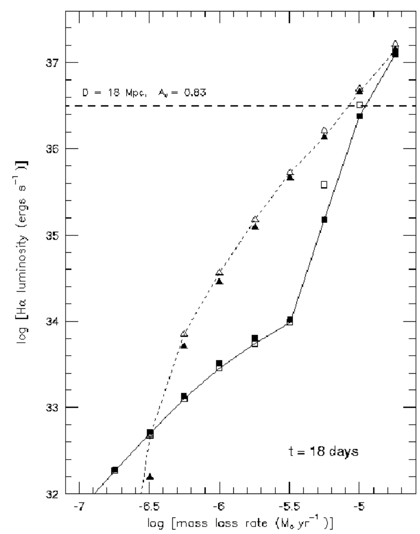

Fig. 2. Hα luminosity at 18 days after the explosion as a function of mass loss rate, assuming $v_w = 10$ km s^{-1}and cosmic abundances. Triangles show models for which ionizing radiation is only produced by the reverse shock, while in models marked by squares we have also included the photospheric emission from the model w7jzl155.ph [2]. Filled symbols are for temperature equipartition between electrons and ions behind the reverse shock, whereas for open symbols the electron temperature is $\frac{1}{2}\times$ the reverse shock temperature. The observed limit for SN 2001el, '18 Mpc, A$_V = 0.83$', is also shown.

epoch we assume that the maximum velocity of the ejecta is $V_{ej} = 4.5 \times 10^4$ km s^{-1}. At 1 day, the velocities of the circumstellar shock and the reverse shock going into the ejecta are $V_s \sim 4.5 \times 10^4$ km s^{-1} and $V_{rev} \sim 1.1 \times 10^4$ km s^{-1}, respectively.

The ionizing radiation from the interaction region consists of free-free emission from the shocked ejecta and circumstellar gas, and photospheric radiation [1, 2, 12] Comptonized by hot electrons in the shocked gas. To model the time dependent ionization and temperature structure of the unshocked circumstellar gas we use an updated version of the code used in [6, 11, 12]. Models were made for values of $\dot{M}$ in the range $(1-300)\times 10^{-7}$ M$_\odot$ yr^{-1}, assuming $v_w = 10$ km s^{-1}. For low mass loss rates, the photospheric radiation dominates the ionization, and its soft photons heat the wind to temperatures in the range $(0.5-5)\times 10^4$ K, whereas for $\dot{M} \gtrsim 5\times 10^{-6}$ M$_\odot$ yr^{-1}, the ionizing radiation from the reverse shock becomes more important, heating the wind close to the shock to $\gtrsim 7\times 10^4$ K. Figure 2 shows the line emission produced in models with different wind densities. Using our derived limits on the Hα luminosity for SN 2001el at the third epoch, we obtain (for cosmic abundances and $v_w = 10$ km s^{-1}) a wind density described by $\dot{M} \sim 1\times 10^{-5}$ M$_\odot$ yr^{-1}, i.e., similar to our limit for SN 2000cx [12]. Such a low limit for the circumstellar gas, as well as other similar limits in the radio and X-rays for other SNe Ia (cf. Ref. [12]), contrasts the recently reported strong Balmer line emission from the SN Ia 2002ic by Hamuy et al. [7]. The observations of SN 2002ic have been used both in favor [9] and against [5] a merger scenario. While the true nature of SN 2002ic is still under debate, detection of early, faint circumstellar line emission in a SN Ia, with temporal variation in the line profiles, would be stronger evidence for a non-merger scenario. Finally, we note that the mass loss rate in symbiotic systems is in the range $10^{-7} - 2 \times 10^{-5}$ $M_\odot$ yr^{-1} [14]. Our results do not support that systems at the upper end of this interval are progenitors of normal SNe Ia.

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