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Binary White Dwarfs in the Supernova Ia Progenitor Survey

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Abstract. We report results of a systematic radial velocity survey for double degenerate (DD) binaries as potential progenitors of type Ia supernovae: SPY (ESO Supernovae Ia Progenitor surveY). More than 1000 white dwarfs (WDs) and pre-white dwarfs were observed with the VLT. The aim of SPY is to perform a statistically significant test of the DD scenario. We give an overview of the project and follow-up results. The sample is used for two tests of the contemporary picture of close binary evolution leading to DDs. It is shown that the SPY observations of low mass He-core WDs (HeWDs) are inconsistent with the idea that they all reside in close binary systems. We carry out a model atmosphere analysis of WDs residing in double-lined binaries and estimate individual cooling ages. For a number of systems the younger (and hotter) component is the less massive one, as expected. However, for some systems the mass ratio is inverted.

1. The Supernovae Ia Progenitor Survey

Supernovae of type Ia (SN Ia) play an outstanding role for our understanding of galactic evolution and the determination of the extragalactic distance scale. However, the nature of their progenitors is not yet settled (e.g. Livio 2000). Several possible progenitor channels have been identified. In the so-called double degenerate (DD) scenario (Webbink 1984; Iben & Tutukov 1984) the SN Ia explosion is triggered by the merging of two white dwarfs (WDs) with a combined mass exceeding the Chandrasekhar limit.

Close DDs radiate gravitational waves, which results in a shrinking orbit due to the loss of energy and angular momentum. If the initial separation is small enough (orbital periods below $\approx$10 h), a DD system could merge within a Hubble time, and if the combined mass exceeds the Chandrasekhar limit the DD would qualify as a potential SN Ia progenitor. Several systematic radial velocity (RV) searches for DDs have been undertaken starting in the mid 1980's checking a total of $\approx$200 white dwarfs RV for variations (cf. Marsh 2000, and references therein), but have failed to reveal any massive, short-period DD progenitor of SN Ia. However, this is not unexpected, as theoretical simulations suggest that only a few percent of all DDs are potential SN Ia progenitors (Iben et al. 1997; Nelemans et al. 2001). In order to perform a definitive test of the DD scenario we embarked on a large spectroscopic survey of $\approx$1000 WDs (ESO **S**N Ia **P**rogenitor surve**Y** – SPY). SPY has overcome the main limitation of all efforts so far to detect DDs that are plausible SN Ia precursors: the samples of surveyed objects were too small.

Spectra were taken with the high-resolution UVES spectrograph of the UT2 telescope of the ESO VLT in service mode. Our instrument setup provided nearly complete spectral coverage from 3200 Å to 6650 Å with a resolution $R = 18500$ (0.36 Å at Hα). Due to the nature of the project, two spectra at different, "random" epochs separated by at least one day were observed. We routinely measure RVs with an accuracy of $\approx 2\,\mathrm{km\,s^{-1}}$ or better, therefore running only a very small risk of missing a merger precursor, which have orbital velocities of $150\,\mathrm{km\,s^{-1}}$ or higher. A total of 1014 stars were observed. A detailed description of the SPY project can be found in Napiwotzki et al. (2001, 2003a). Results of follow-up campaigns to determine the orbital periods of the RV variable binaries are presented in Napiwotzki et al. (2005) and Nelemans et al. (2005). Determinations of masses and orbital periods are summarised in Fig. 1.

2. Helium-Core White Dwarfs

Low mass WDs with masses $0.45M_\odot$ or less (further-on called HeWDs) are below the critical mass for a core helium flash on the red giant branch (Sweigart & Gross 1978). These WDs usually possess a helium core, some might be of hybrid type with a C/O core and a thick He mantle. Since in both cases binary evolution is necessary to explain their formation, we expect to observe a high fraction of DDs.

We carried out Balmer line fitting of all DA white dwarfs from the SPY sample (cf. Koester et al. 2001) and derived temperatures, gravities and masses.

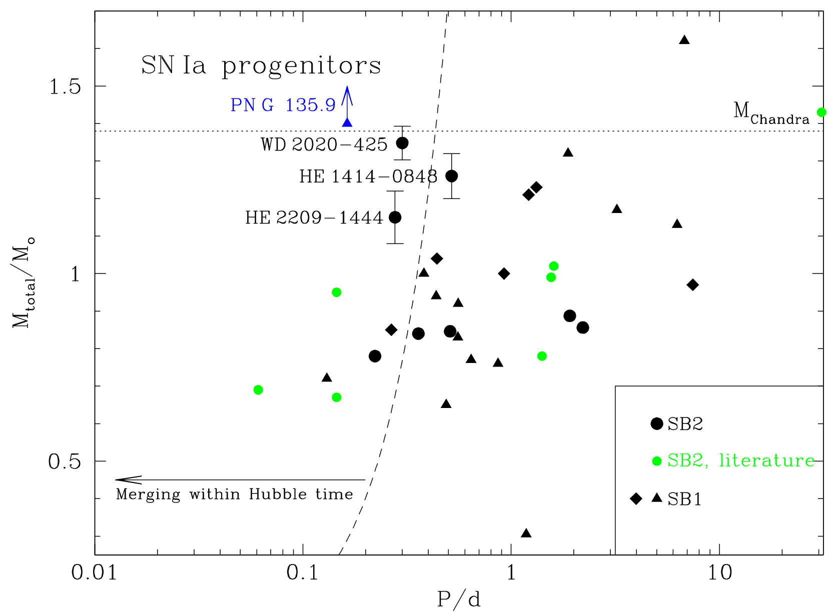

Figure 1. Periods (P) and system masses ($M_{\rm total}$) determined from follow-up observations of DDs from SPY. Results for double-lined systems are compared to previously known systems. The other DD systems are single-lined (triangles: WD primaries; diamonds: sdB primaries). The masses of the unseen companions are estimated from the mass function for the expected average inclination angle ($i = 52°$). PN G135.9+55.9 is a serendipitously discovered DD, the central star of a planetary nebulae (Tovmassian et al. 2004; Napiwotzki et al. 2005).

The SPY sample contains 26 HeWDs with masses smaller than $0.42M_\odot$, safely below the mass limit for normal C/O WDs. SPY detected 11 RV variable binaries among those 26 HeWDs, i.e. a binary fraction of 42%. If we restrict ourselves to the single-lined (SB1) systems with invisible companions, the binary fraction decreases to 8 out of 23 or 35%.

This indicates a high frequency of close binaries HeWDs, much higher as found for C/O white dwarfs. However, independent of which number we adopt, this is well below the expected rate close to 100%. How much of this deficit can be explained by non-detections caused by unfavourable inclination angles and phases during the observations? We performed a Monte-Carlo simulation of the detection probability. Detection probabilities for individual HeWDs were computed using the timing of the observations and their RV error limits. The result for the co-added sample are plotted as effective sample size in Fig. 2.

The effective sample size can be read as the number of RV variable systems we should detect in a sample consisting of 100% binaries for a given period. The plot shows how numbers depend on the adopted companion mass. A mass of $0.5M_\odot$ corresponds to a typical WD companion. It is expected that the vast majority of binaries have periods $P < 10\,$d after the common envelope event (Nelemans et al. 2001). Predicted numbers of detections are 20 and 18 for $0.5M_\odot$ white dwarf and $0.2M_\odot$ M dwarf companions (Table 1). Both are at variance

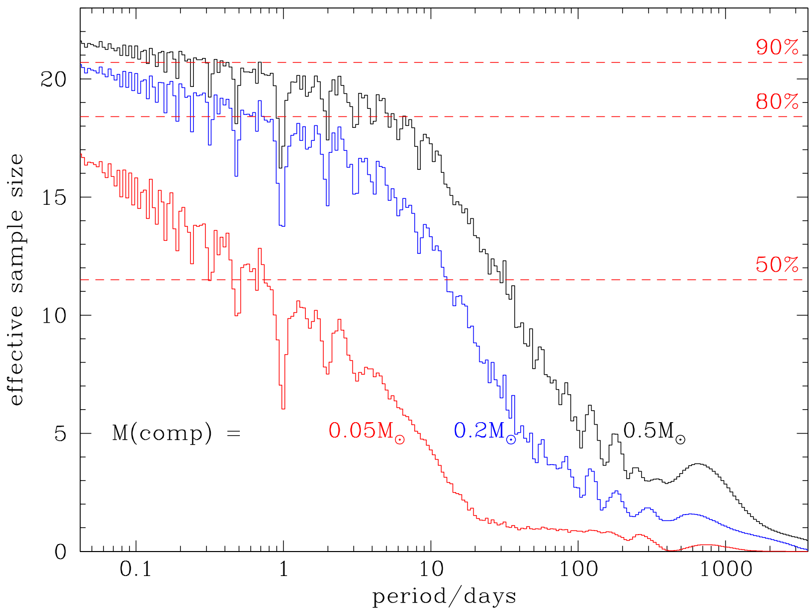

Figure 2. Effective sample size (= number of WDs times detection probability) as a function of period for different companion masses. The dashed lines indicate the detection probability in percent.

Table 1. Number of RV variable systems, which should have been detected for a 100% close binary HeWD sample. Numbers are given for systems with periods P below 10 d and for the brown dwarf case below 1 d.

companion type	M_{comp} $[M_\odot]$	$P < 10\,\mathrm{d}$	$P < 1\,\mathrm{d}$
white dwarf	0.5	20	
M star	0.2	18	
brown dwarf	0.05	11	14

with the observed numbers. Can this riddle be solved by assuming brown dwarf companions, which are more difficult to detect? Table 1 shows that even for a $0.05M_\odot$ brown dwarf companion we should have detected RV variation in 11 HeWDs vs. 8 observed detections. However, this could be marginally explained by statistical fluctuations. However, one has to take into account that a brown dwarf companion will very likely end up in a very close system with $P < 1\,\mathrm{d}$ after the common envelope systems as exemplified by the WD 0137−349 system ($P = 116\,\mathrm{min}$; Maxted et al. 2006, and these proceedings). This boosts the expected number to 14 (Table 1), incompatible with the observed sample.

3. Parameters of Double-Lined DDs

Most DDs in our sample (and other samples) are single-lined (SB1), i.e. the companion has already cooled down to invisibility. However, spectral features of both DD components are visible in some systems, i.e. these are double-lined spectroscopic binaries (SB2). On the one hand the analysis is more complicated for double-lined systems, but on the other hand the spectra contain more information than spectra of single-lined systems. The RVs of both WDs can be measured, and the orbits of both individual components can be determined. The ratio of velocity amplitudes and the gravitational redshift difference can be determined and combined to derive mass for both individual components (Napiwotzki et al. 2002).

An alternative approach is a fit of the line profiles with model spectra determine the fundamental parameters, effective temperature and surface gravity of the stars. This has become a standard method for single white dwarfs (cf. a number of contributions on these proceedings), but the analysis is more difficult for double-lined binaries, for which the observed spectra are a superposition of the spectra of both stars, whic require a different approach.

We developed the programme FITSB2 (Napiwotzki et al. 2004), which performs a spectral analysis of both components of double-lined systems. It is based on a χ^2 minimisation technique using a simplex algorithm. *The fit is performed on all available spectra covering different spectral phases simultaneously*, i.e. all available spectral information is combined into the parameter determination procedure. This method was tested for the double-lined binary HE 1414−0848. Both methods, the gravitational redshift and the model atmosphere approach, yielded results, which were in good agreement (Napiwotzki et al. 2003b).

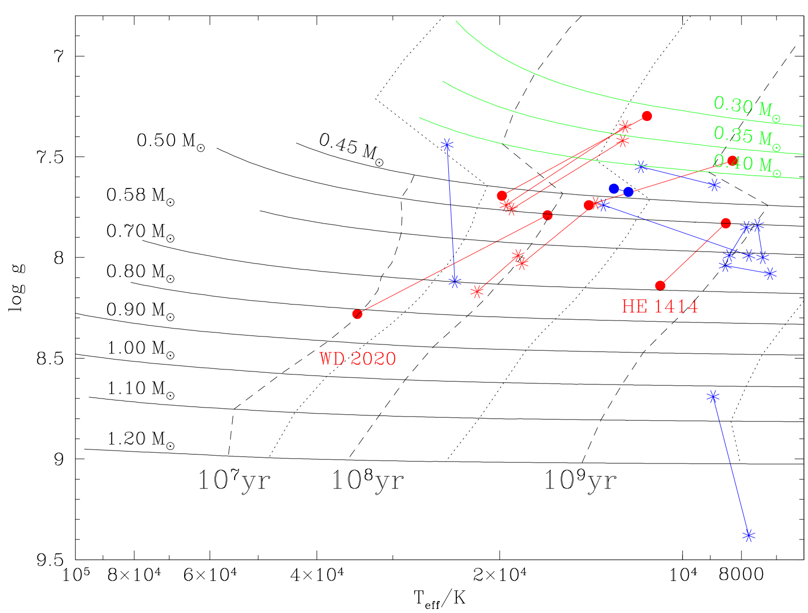

Figure 3. Components of double-lined DDs in the $T_{\rm eff}$–$\log g$ diagram. Results for the binaries (connected by lines) with a full orbital solution are plotted as filled circles and as asterisk for other systems. We used the cooling tracks of Benvenuto & Althaus (1999) and computed isochrones for the cooling age (vertical lines labelled with age).

The parameters $T_{\rm eff}$ and $\log g$ determined by the spectral fitting with FITSB2 allows another test of close binary evolution. These parameters can be compared with WD cooling tracks in the $T_{\rm eff}$–$\log g$ plane (Fig. 3).

What is expected? Population synthesis calculations predict that most DDs evolved through two common envelope phases (Nelemans et al. 2001), in which the red giant envelope is ejected and the orbital separation of both stars decreases, often dramatically. As a result the red giant evolution of the second star is terminated at an earlier phase than for the first star and the second white dwarf has a lower mass. Thus it is expected that the younger (and usually hotter) WD in a DD is less massive.

Fig. 3 shows that this is indeed the case for a number of binaries. However, for some DDs, most significantly WD 2020−425 and HE 1414−0848, the mass ratio is inverted: the more massive WD is hotter. These systems could be understood, if the first phase of interaction involved conservative mass transfer instead of common envelope. Evolution of this type is expected for some DD precursors (e.g. the scenario in Fig. 1, bottom right in Nelemans et al. 2001), alas it is predicted that the resulting system contains one very low mass HeWD. However, both components of WD 2020−425 and HE 1414−0848 are more massive C/O WDs. Taking into account that both WD 2020−425 and HE 1414−0848 are among the highest mass DD systems known (Fig. 1) our findings might indicate that an important channel for the formation of near-Chandrasekhar mass DDs is not properly taken into account in current simulations.

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