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New Results from the Supernova Ia Progenitor Survey

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Abstract. We report on 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 and pre-white dwarfs were observed with the VLT. Our aim is to perform a statistically significant test of the DD scenario. SPY detected more than 100 new binary white dwarfs, dramatically increasing the number of known DDs. System parameters are determined from ongoing follow-up observations. Our sample includes systems with masses close to the Chandrasekhar limit and a probable SN Ia progenitor candidate.

Introduction

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 ≈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 ≈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).

The SPY Project

In order to perform a definitive test of the DD scenario we embarked on a large spectroscopic survey of ≈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 UV-Visual Echelle Spectrograph (UVES) of the UT2 telescope (Kueyen) 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 detailed description of the SPY project can be found in Napiwotzki et al. (2001, 2003a).

The last survey observations were taken in March 2004. A total of 1014 stars were observed. This corresponds to 75% of the known WDs accessible by VLT and brighter than $B = 16.5$. SPY detected ≈100 new DDs, 16 of which are double-lined systems (only 6 were known before). The great advantage of double-lined binaries is that they provide us with a well determined total mass (cf. below). Our sample includes many short period binaries, several with masses closer to the Chandrasekhar limit than any system known before, including one possible SN Ia progenitor candidate (cf. Fig. 2). In addition, we detected 19 RV variable systems with a cool main sequence companion (pre-cataclysmic variables).

Although important information like the periods, which can only be derived from follow-up observations, are presently lacking for most of the stars, the large sample size already allows us to draw some conclusions. The fundamental WD parameters like masses are known from spectral analysis (Koester et al. 2001). Fig. 1 shows a SPY subsample of bright DAs ($V \leq 15.5$) in the temperature-gravity plane. DDs are indicated. The bright subsample consists of 286 observed DAs, i.e. 96% of all known DAs with $V \leq 15.5$ and $\delta < 25°$. The distribution of white dwarfs follows the usual pattern with most clustering in the mass interval $M = 0.5 \ldots 0.6 M_\odot$. Most white dwarfs with masses higher than $0.45 M_\odot$ have a

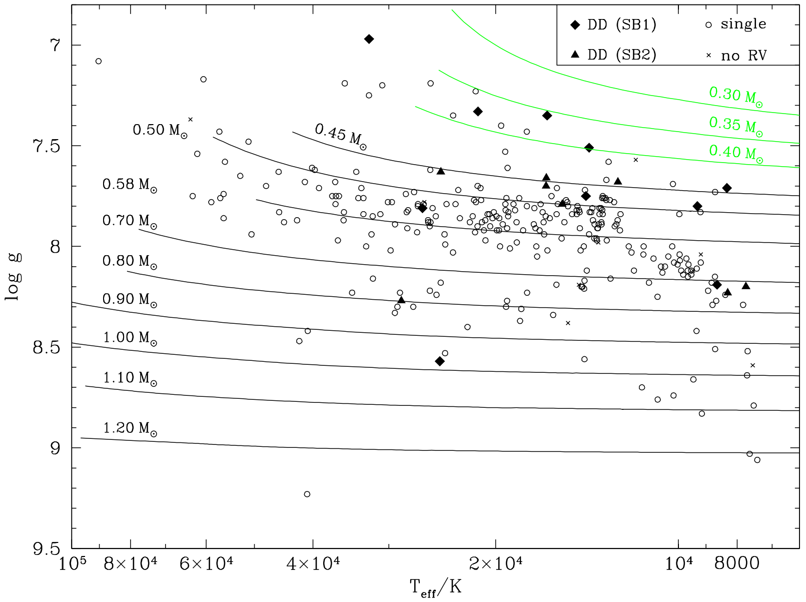

Figure 1. The bright subsample of 286 DAs in the $T_{\rm eff}/\log g$ diagram.DDs are indicated. The white dwarf parameters are compared to cooling tracks from Benvenuto & Althaus (1999).

C/O core and are well explained by single star evolution. We detected 11 DDs in this mass range, which corresponds to a DD fraction of ≈5%.

The situation is different for WDs with masses below $0.45 M_\odot$, the lower limit for the ignition of a helium flash in red giants. These WDs possess either a helium core or a C/O core and a thick He mantle. Since binary evolution is necessary to explain their formation, a high fraction of DDs is expected. We detect seven DDs among our sample of twenty low mass WDs. This is a high fraction, indeed, but it is much lower than a value close to 100% as expected according to the simple picture.

Parameters of double degenerates: Follow-up observations of this sample are mandatory to exploit its full potential. Periods and WD parameters must be determined to find potential SN Ia progenitors among the candidates. The secondary of most DD systems has already cooled down to invisibility. These DDs are single-lined spectroscopic binaries (SB1). Our spectroscopic follow-up observations allow us to determine the orbit of the primary component (i.e. the period P and the RV amplitude K_1). The mass of the primary M_1 is known from a model atmosphere analysis (Koester et al. 2001). Constraints on the mass of the secondary M_2 can be derived from the mass function. For a given inclination angle i the mass of the secondary can be computed. However, i is rarely known, but the result for $i = 90^\circ$ yields a lower mass limit. For a statistical analysis it is useful to adopt the most probable inclination $i = 52^\circ$. We have plotted the single-lined systems with the resulting system mass in Fig. 2. Note that two SB1 binaries have probably combined masses in excess of the Chandrasekhar limit.

However, the periods are rather long preventing merging within a few Hubble times.

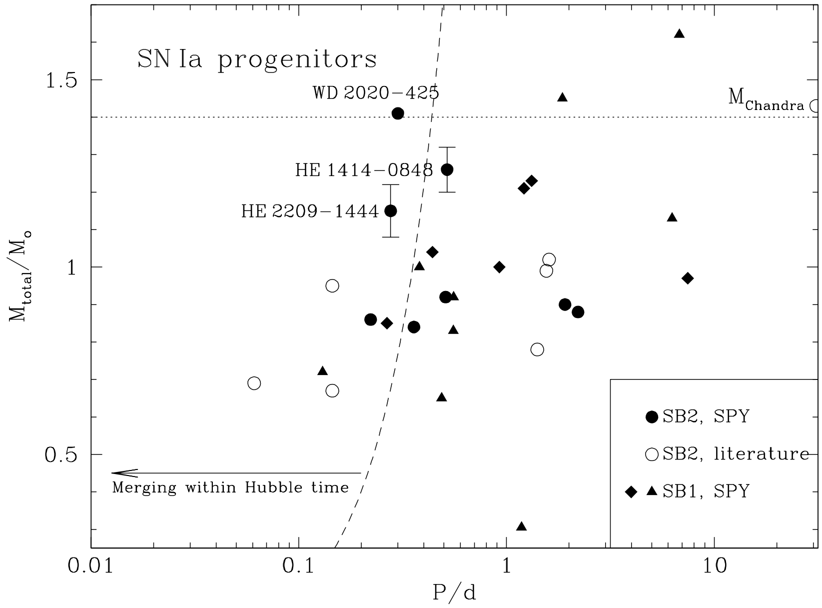

Figure 2. Periods (P) and system masses ($M_{\rm total}$) determined from follow-up observations of DDs from SPY. Results for double-lined systems are compared to previously known systems. The other DD systems are single-lined (triangles: WD primaries; diamonds: sdB primaries). The masses of the unseen companions are estimated from the mass function for the expected average inclination angle ($i = 52°$).

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 is directly related to the mass ratio of both components: $M_2/M_1 = K_1/K_2$. However, additional information is needed before the absolute masses can be determined. There exist two options to achieve this goal in double-lined DDs. The mass dependent gravitational redshift of WDs causes a measurable difference of the mean "velocity" of the individual components. For a given mass-radius relation gravitational redshifts can be computed as a function of mass. Since the mass ratio is already known from the amplitude radio, only one combination of masses can fulfil both constraints. Napiwotzki et al. (2002) used this method to show that the DD HE 1414−0848 has a combined mass of $1.26 M_\odot$, only 10% below the Chandrasekhar limit (Fig. 2).

This method cannot be used if the system consists of WDs of low mass, for which the individual gravitational redshifts are small, or if their masses are too similar, because the redshift differences are very small. Another method, which works in these cases as well, is the model atmosphere analysis of the spectra to determine the fundamental parameters, effective temperature and surface gravity of the stars. Because these systems are double-lined the spectra are a superposition of both individual WD spectra. Therefore we developed the programme FITSB2, 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. We used our spectra of HE 1414−0848 for a test of this method. Both methods, the gravitational redshift and the model atmosphere approach, yielded results, which were in good agreement (Napiwotzki et al. 2003b).

Systems of special interest: The double-lined system WD 2020−425 is probably a SN Ia progenitor (Fig. 2). It consists of two hot DAs (≈34000 K and ≈17000 K). However, the RV curve of the hotter component is very difficult to measure causing relatively large uncertainties. We could get a good parameter estimate for the hot component from a FUSE spectrum of WD 2020−425. This allowed us to improve our estimate of temperature and gravity of the cooler component from the optical spectrum. Our results imply a combined mass of the binary of $1.41 M_\odot$, just above the Chandrasekhar limit. We are currently in the process of finalising this analysis.

A small number of DAs display He I lines in their spectra as well. They are classified as DABs. Wesemael et al. (1994) performed a spectral analysis of two newly discovered DABs: MCT 0128-3846 and MCT 0453-2933. Wesemael et al. could show that a consistent fit of the optical lines and the UV/optical energy distribution of the two DABs is only possible if composite spectra of a DA and a DB are assumed.

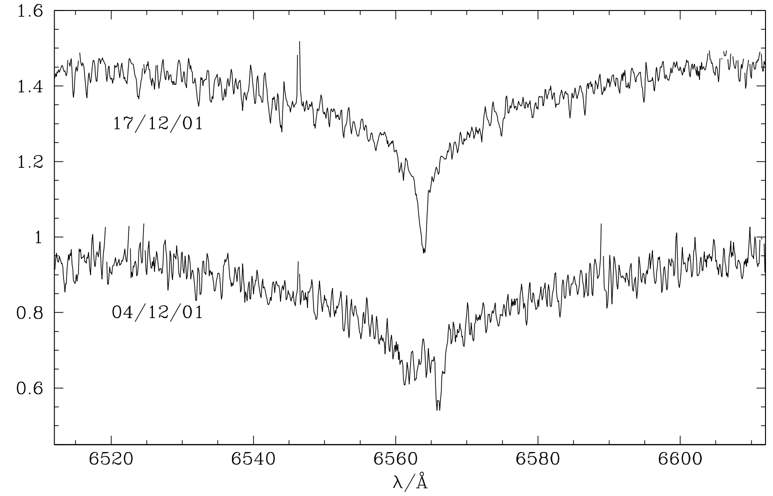

Figure 3. Two Hα spectra of the “DAB” MCT 0453−2933 observed during different nights. The lower spectrum shows a clear splitting of the line profile into two different components.

We observed both "DABs" in the course of the SPY project. We found no signs of RV variability for MCT 0128−0346, indicating that this is probably a long period system. However, MCT 0453−2933 is a short period DD (0.358d). Two components are visible in the Hα profile, indicating that the DB component of this system is a DBA with a relatively high abundance of hydrogen in its atmosphere.

Concluding remarks: The survey part of SPY has now been completed. We increased the number of WDs checked for RV variability from 200 to 1000 and increased the number of known DDs to more than 100. Our sample includes many short period binaries (Fig. 2), several with masses closer to the Chandrasekhar limit than any system known before, greatly improving the statistics of DDs.

Apart from the direct detection of DD precursors of SN Ia SPY will also provide a census of the final binary configurations. This is an important test for the theory of close binary star evolution after mass and angular momentum losses through winds and common envelope phases, which are very difficult to model. An empirical calibration provides the most promising approach. A large sample of binary WDs covering a wide range in parameter space is the most important ingredient for this task.

Our ongoing follow-up observations already revealed the existence of three short period systems with masses close to the Chandrasekhar limit, which will merge within 4 Gyrs to two Hubble times. Even if it will finally turn out that the mass of our most promising SN Ia progenitor candidate system is slightly below the Chandrasekhar limit, our results already allow a qualitative evaluation of the DD channel. Since the formation of a system slightly below Chandrasekhar limit is not very different from the formation of a system above this limit, the presence of these three systems alone provides evidence (although not final proof) that potential DD progenitors of SN Ia do exist.

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