

SPY – The ESO Supernovae Type Ia Progenitor Survey

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Supernovae and their progenitors

Supernovae (SNe) mark the violent termination of a star's life in an explosion. They are classified according to their light curve as type I or II, with the type I SNe producing very similar light curves, while the SNe type II are more diverse. Spectroscopic observations reveal the presence of hydrogen in SNe type II, while no hydrogen lines are detectable in SNe type I. According to their spectral appearance the type I class can be further subdivided into Ia, Ib, and Ic.

SNe type II and Ib,c are observed only in spiral galaxies and irregular galaxies containing young stellar populations. This indicates that their progenitors are short-lived massive stars (masses above $8 M_{\odot}$). Indeed, the occurrence of SN explosions and the formation of a neutron star remnant at the end of the nuclear lifetime of a massive star are now relatively well understood processes.

However, the question of SN Ia progenitors is not yet settled (e.g. Livio

2000). SN Ia are observed in all types of galaxies, including elliptical galaxies containing only old stellar populations. The light curves of SN Ia are dominated by the decay of the radioactive material synthesized in the explosion (mainly nickel). The ^{56}Ni isotope sits at the top of a decay chain leading to ^{56}Co (half-life 6.1 days) and to stable ^{56}Fe (half-life 77 days). The rapid evolution of SN Ia light curves indicates that the precursors of these supernovae must be compact objects of small mass with very little mass holding back the gamma-rays produced by the radioactive decay. The only candidate, which can fulfill the observational constraints, is the thermonuclear explosion of a white dwarf.

Since type Ia supernovae were identified as excellent distance indicators for cosmology and have provided indications of cosmic acceleration, it is extremely important to have a better understanding of their explosions and the systems that lead up to them. While it is possible to test the quality of the distance indicator in the nearby universe by checking the linear Hubble expansion, one has to rely on the accuracy of the distance indicator to go beyond the linear Hubble flow and probe the redshift regime, where the cosmological models differ in their predictions. At this point, other signatures of the reliability of the distance indicator have to be secured. With lookback times of about half

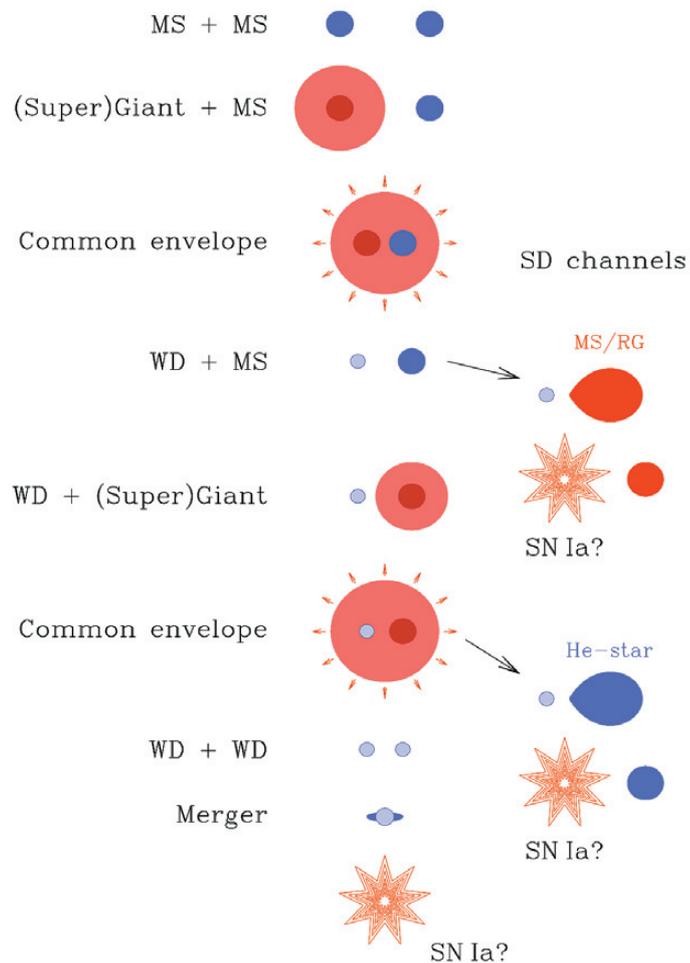


Figure 1: Possible evolutionary channels for the formation of a SN Ia progenitor via the double degenerate (DD) and the single degenerate (SD) scenarios. In both scenarios the evolution starts with a binary of two main sequence (MS) stars. The more massive star becomes a red giant and its envelope is ejected in a common envelope event. In the DD scenario the second MS star evolves to a red giant with a second common envelope event and the formation of a close binary of two white dwarfs (WD). If the DD system is close enough and massive enough, gravitational wave radiation will cause it to merge and explode as a SN Ia. In the two variants of the SD scenario the secondary fills its Roche lobe while i) close to the main sequence or as red giant (RG) or ii) as a He-star after another common envelope phase. Mass is transferred onto the WD star and increases the WD mass until the Chandrasekhar limit is reached. Note that the SD scenarios predict the survival of the companion star.

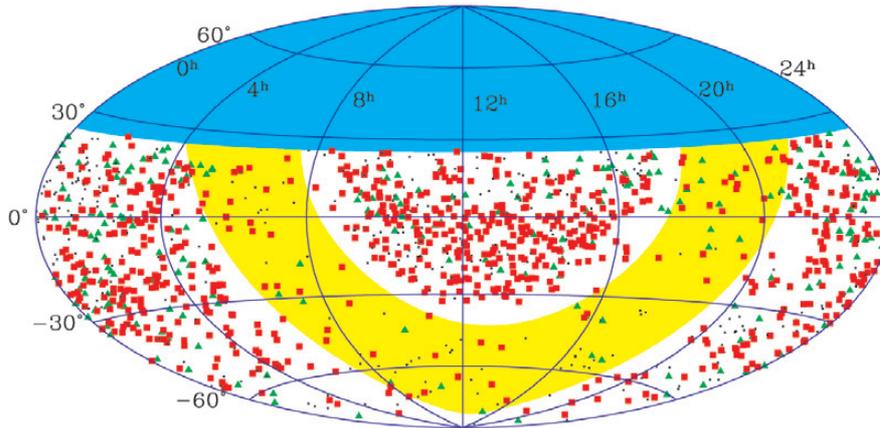


Figure 2: Distribution of all known white dwarfs south of $\delta = +25^\circ$ and brighter than $V = 16.5$. Red squares indicate white dwarfs with two spectra taken by SPY. A second spectrum remains to be collected for the green triangles, while the black dots are the remaining objects without a SPY observation. The yellow band indicates the position of the Galactic disk ($|b| < 20^\circ$).

the current age of the universe, one has to make sure that evolution of the distance indicator is not mimicking a cosmological effect. To do this reliably one has to try to understand the distance indicator in as many aspects as possible. One of the shortcomings of type Ia supernovae is our ignorance of the progenitor systems and the exact explosion mechanism. By identifying these progenitors we should be able to constrain possible evolutionary effects on the cosmological result.

While the cosmic microwave background experiments have provided a phenomenal accuracy of the integrated cosmological parameters, they cannot provide the more detailed measurements to explore the expansion history of the universe, i.e. the equation of state parameter. Only distance indicators, like type Ia supernovae, can yield this information. But the systematics of these derivations have to be assessed as precisely as possible. The knowledge of the precursor state and the physics of the transformation to the supernova are hence vital ingredients for our understanding of cosmology.

Most stars (i.e. all stars with a mass below about 8 solar masses) will end their lives as white dwarfs. These are small cooling bodies consisting mainly of carbon and oxygen with thin layers of hydrogen and/or helium on top, supported by degenerate electron gas. They will cool for billions of years and disappear as small cold clumps into the cosmic background without signs of their once glorious lives. Some white dwarfs will, however, destroy themselves in a gigantic thermonuclear explosion. To do so, they have to be forced into a density and temperature regime, where carbon and oxygen burn explosively and disrupt the star. Above the Chandrasekhar mass ($1.4 M_\odot$) the electron degeneracy can no longer support white dwarfs. At this point the white dwarf either has to collapse to a neutron star or explode as a supernova. Since

no physical process is known which leads to such conditions in a single white dwarf, a companion star has to help. This general picture of binary white dwarfs as the progenitor stars for type Ia supernovae is the most commonly held view today.

The growth of a white dwarf to Chandrasekhar mass is a long-standing problem of observational astrophysics. Several channels have been identified as possibly yielding such a critical mass (Fig. 1). They can broadly be grouped into two classes (e.g. Livio 2000). The single degenerate (SD) channel in which the white dwarf is accompanied by a regular star, either a main se-

quence star, a (super)giant, or a helium star, as mass donor and the double degenerate (DD) channel where the companion is another white dwarf. 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 close 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.

The double degenerate scenario for the progenitors was proposed many years ago. So far, no SN Ia progenitor has been identified, which is not really

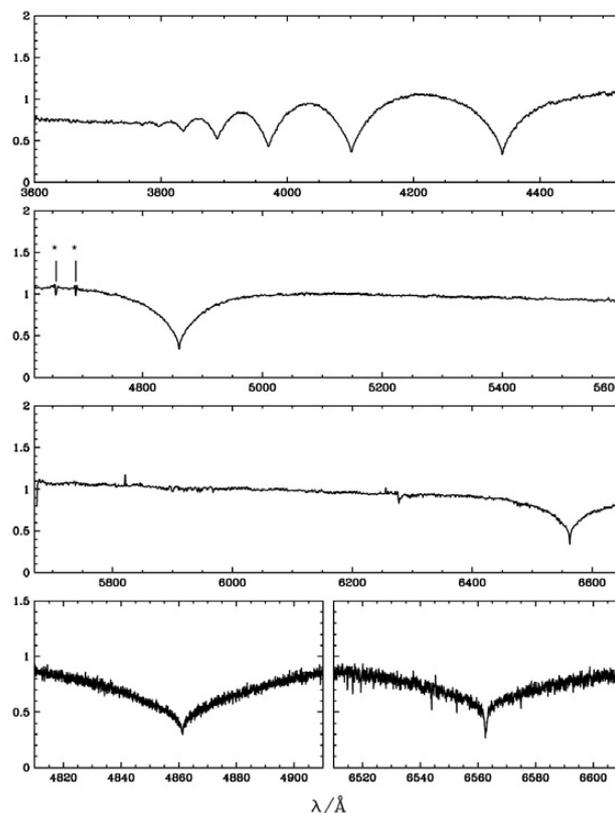


Figure 3: UVES spectrum of the DA white dwarf WD 1026+023. The upper three panels correspond to the blue channel and to both parts of the red channel covered by different CCDs. The spectra were smoothed to a resolution of 1 \AA . Two reduction artifacts are indicated by asterisks. The lower panel shows the unbinned spectra of the $H\alpha$ and $H\beta$ line cores.

surprising considering the rareness of SNe Ia and the small volume that can be surveyed for white dwarfs. The orbital velocity of white dwarfs in potential SN Ia progenitor systems must be large (>150 km/s) making radial velocity (RV) surveys of white dwarfs the most promising detection method. Several systematic RV searches for DDs were undertaken starting in the mid 1980's. Before 2001, combining all the surveys, ~ 200 white dwarfs were checked for RV variations with sufficient accuracy yielding 18 DDs with periods $P < 6.3$ d (Marsh 2000 and references therein). None of the 18 systems seems massive enough to qualify as a SN Ia precursor. This is not surprising, as theoretical simulations suggest that only a few percent of all DDs are potential SN Ia progenitors (Iben, Tutukov & Yungelson 1997; Nelemans et al. 2001). It is obvious that larger samples are needed for statistically significant tests.

The surveys mentioned above were performed with 3–4-m class telescopes. A significant extension of the sample size without the use of larger telescopes would be difficult due to the limited number of bright white dwarfs. This situation changed after the ESO VLT became available. In order to perform a definitive test of the DD scenario we have embarked on a large spectroscopic survey of more than 1000 white dwarfs using the UVES spectrograph at the UT2 telescope (Kueyen) of VLT to search for RV variable white dwarfs (ESO SN Ia Progenitor survey – SPY). SPY will 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.

The survey

As outlined above, we need a very large input sample of white dwarfs, which are bright enough ($B \leq 16.5$) to take high-resolution spectra with a sufficiently high signal-to-noise ratio. The most complete catalogue of spectroscopically confirmed white dwarfs is the actual version of the McCook & Sion (1999) catalogue. However, it contains “only” 918 white dwarfs brighter than $B = 16.5$ south of $\delta = +25^\circ$. Since we needed a larger input sample, we added more objects from recent surveys: the *Hamburg-ESO survey (HES)*, the *Hamburg-Quasar survey (HQS)*, the *Montreal-Cambridge-Tololo survey (MCT)*, and the *Edinburgh-Cape survey (EC)*. A map of all known white dwarfs (observed and unobserved by SPY) fulfilling our criteria is shown in Fig. 2. A striking feature is a lack of white dwarfs in the Galactic plane. This cannot be explained by interstellar extinction, because bright white dwarfs are nearby objects. However, all major surveys during the last decades (including the surveys mentioned above) were aimed at

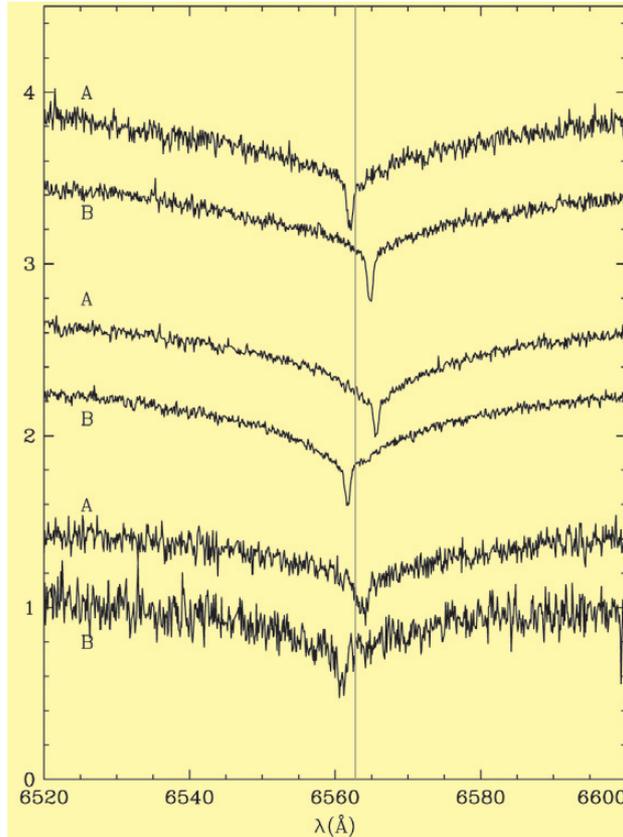


Figure 4: Three single-lined RV variable DDs from our VLT survey. The vertical line marks the rest wavelength of $H\alpha$. The spectra are slightly rebinned (0.1 \AA) without degrading the resolution.

the detection of galaxies and quasars and restricted to high Galactic latitudes.

Spectra were taken with the UV-Visual Echelle Spectrograph (UVES) of the UT2 telescope (Kueyen) of the ESO VLT. UVES is a high resolution Echelle spectrograph, which can reach a resolution of 110,000 in the red region with a narrow slit. Our instrument set-up (Dichroic 1, central wavelengths 3900 Å and 5640 Å) uses UVES in a dichroic mode. Nearly complete spectral coverage from 3200 Å to 6650 Å with only two roughly 80 Å wide gaps at 4580 Å and 5640 Å is achieved.

Our programme was implemented as a large programme in service mode. It takes advantage of those observing conditions, which are not usable by most other programmes (moon, bad seeing, clouds) and keeps the VLT busy when other programmes are not feasible. A wide slit (2.1") is used to minimize slit losses and a 2×2 binning is applied to the CCDs to reduce read out noise. Our wide slit reduces the spectral resolution to $R = 18,500$ (0.36 \AA at $H\alpha$) or better, if seeing discs were smaller than the slit width. Depending on the brightness of the objects, exposure times between 5 min and 10 min were chosen. The S/N per binned pixel (0.03 \AA) of the extracted spectrum is usually 15 or higher. Due to the nature of the project, two spectra at different, “random” epochs separated by at least one day are observed.

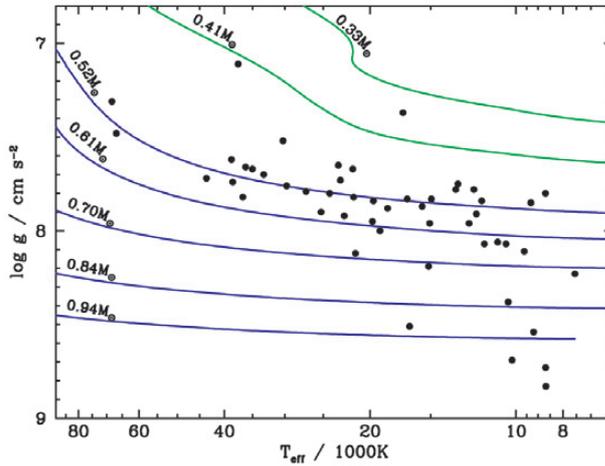
ESO provides a data reduction pipeline for UVES, based on MIDAS procedures. The quality of the reduced

spectra is in most cases very good; especially the removal of the interorder sensitivity variation and merging of the orders works very well. Sometimes the reduction pipeline produces artifacts of varying strength, e.g. a quasiperiodic pattern in the red region similar in appearance to a fringing pattern. In a few cases either the blue or the red part of the spectrum has extremely strong artifacts of unknown origin. This pipeline reduction was extremely useful for a fast selection of RV variable DDs for follow-up observations (described below). In the meantime we have produced a semi-automatic set of procedures for the reduction of our UVES spectra. A reduction of the survey data is already completed and yielded a large set of good quality white dwarf spectra.

As an example of the quality achievable the spectrum of a hydrogen-rich DA white dwarf is shown in Fig. 3. A characteristic feature of white dwarfs are the very broad spectral lines caused by the high densities in their atmospheres. Obviously, broad lines are very ill-suited for RV measurements. However, deviations from local thermal equilibrium (LTE) produce sharp NLTE cores of the $H\alpha$ lines in the atmospheres of hydrogen-rich DA white dwarfs (Fig. 3), which allow accurate RV measurements. This feature is not present in non-DA white dwarfs (spectral types DB, DO) with hydrogen-poor atmospheres, but the use of several helium-lines enables us to reach a similar accuracy.

Since SPY produces a large number

Figure 5: Mass determination of (single and binary) DA white dwarfs. Temperature and gravity, determined from a model atmosphere analysis of the UVES spectra (Koester et al., 2001) are compared to cooling sequences of white dwarfs (Blöcker et al., 1997) for a range of white dwarf masses.



of spectra, which have to be checked for RV variations, a fast and reliable algorithm to measure RV shifts is necessary. We apply a “cross-correlation” routine based on a χ^2 test (description in Napiwotzki et al. 2001). The RV shift is evaluated from the minimum χ^2 . Error margins can be estimated from the χ^2 statistics as well. One great advantage of our procedure is its flexibility and that it can easily be applied to measure RV shifts in stars of different spectral types (Balmer lines of DA white dwarfs, HeI lines of DBs, HeII and metal lines of hot DO white dwarfs). We routinely measure RVs with an accuracy of about 2 km/s, therefore running only a very small risk of missing a merger precursor, which have orbital velocities of 150 km/s or higher.

The large programme was finished at the end of last semester. A total of 1014 stars were observed (Fig. 2). This corresponds to 75% of the known white dwarfs accessible by VLT and brighter than $B=16.5$. A second spectrum is still lacking for 242 white dwarfs, but time has been granted to complete these observations. Currently we could check 772 stars for RV variations, and detected 121 new DDs, 16 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. Since it is likely that the SPY sample contains even more double-lined systems (with a faint secondary), we will check follow-up observations of apparently single-lined systems for the signature of the sec-

Figure 6: Periods (P) and system masses (M_{total}) determined from follow-up observations of DDs from SPY. Results for double-lined systems (black circles) are compared to previously known systems (green circles). 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 ($i = 52^\circ$).

ondary. Our sample includes many short period binaries (some examples are discussed in the next section), several with masses closer to the Chandrasekhar limit than any system known before. In addition, we detected 19 RV variable systems with a cool main sequence companion (pre-cataclysmic variables; pre-CVs). Some examples of single-lined and double-lined DDs are shown in Fig. 4 and 7. Our observations have already increased the DD sample by a factor of seven. After completion, a final sample of about 150 DDs is expected.

Follow-up observations of this sample are mandatory to exploit its full potential. Periods and white dwarf parameters must be determined to find potential SN Ia progenitors among the candidates. Good statistics of a large DD sample will also set stringent constraints on the evolution of close binaries, which will dramatically improve our understanding of this phase of stellar evolution. During our follow-up observa-

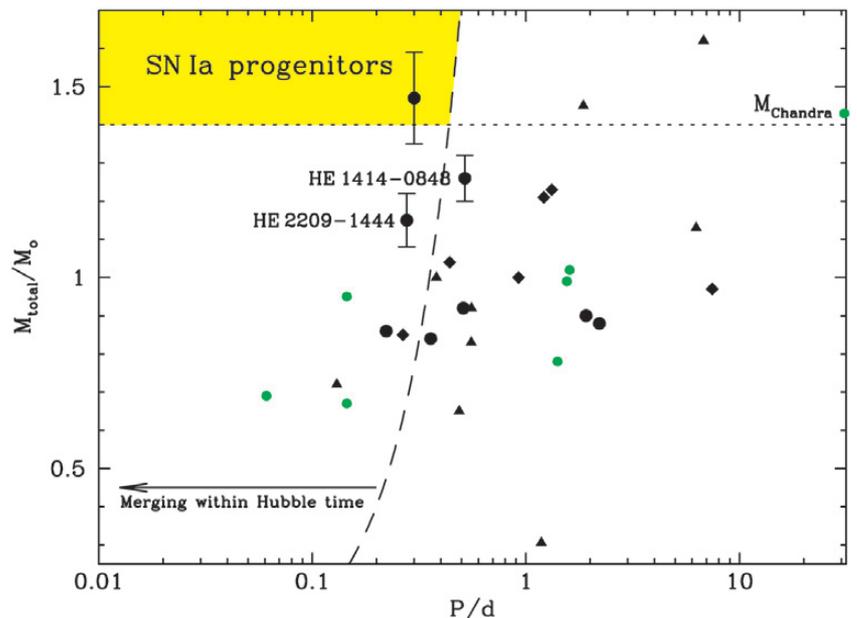
tions we have detected a very promising potential SN Ia precursor candidate. However, some additional observations are necessary to verify our RV curve solution.

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. (Note that fundamental white dwarf parameters like masses are known from the spectral analysis described below). One interesting aspect concerns white dwarfs of non-DA classes (basically the helium-rich spectral types DB, DO, and DZ, in contrast to the hydrogen-rich DAs). SPY is the first RV survey which performs a systematic investigation of both classes of white dwarfs: DAs and non-DAs. Previous surveys were restricted to DA white dwarfs. Our result is that the binary frequency of the non-DA white dwarfs is equal to the value determined for the DA population within the statistical accuracy.

Parameters of double degenerates

Once the binaries in the white dwarf sample have been revealed, follow-up observations are necessary to determine the system parameters of the DDs. We concentrated on candidates with high RV variations, indicating short periods, because the probability to find potential SN Ia candidates is highest among these systems. However, let us note that probably some of the “small RV” DDs could be short period systems (possibly even SN Ia progenitors) with low inclination angles and/or unfavourable phase differences of the SPY observations.

The secondary of most DD systems



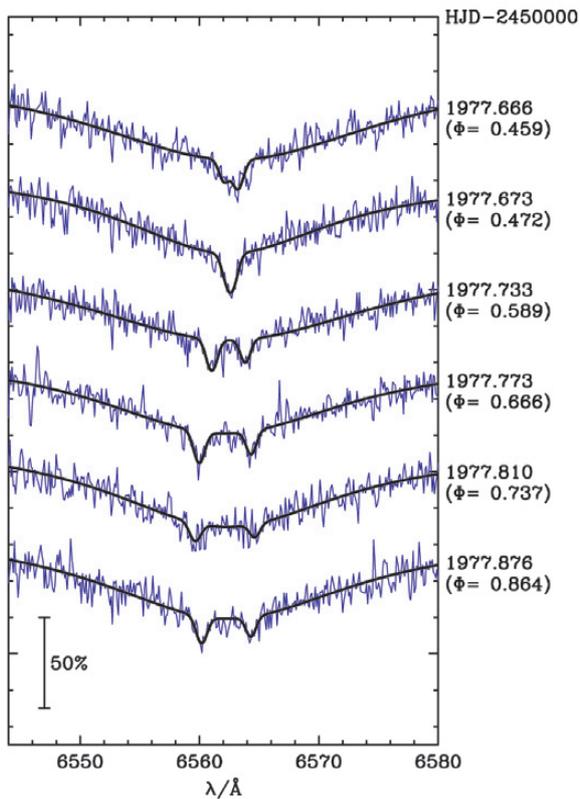


Figure 7: $H\alpha$ spectra of HE 1414-0848 covering 5 hours during one night together with a fit of the line cores. The numbers indicate the Julian date of the exposures and the orbital phase ϕ .

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 radial velocity amplitude K_1). The mass of the primary M_1 is known from a model atmosphere analysis (Fig. 5). Constraints on the mass of the secondary M_2 can be derived from the mass function: $M_2^3 \sin^3 i / (M_1 + M_2)^2 = K_1^3 P / (2\pi G)$. (1)

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. 6. Note that two binaries have probably combined masses in excess of the Chandrasekhar limit. However, the periods are rather long preventing merging within a few Hubble times.

Sometimes spectral features of both DD components are visible (Fig. 7), i.e. these are double-lined spectroscopic binaries (SB2). As an example for other double-lined systems we discuss here the DA+DA system HE1414-0848 (Napiwotzki et al. 2002). On one hand the analysis is 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 white dwarfs can be measured, and the orbits of both individual components can be determined (Fig. 8). For our example HE1414-0848 we derived a period of $P=12^d25^m44^s$ and semi-amplitudes $K_1 = 127$ km/s and $K_2 = 96$ km/s. The ratio of velocity amplitudes is directly related to the mass ratio of both components:

$$M_2 / M_1 = K_1 / K_2 = 1.28 \pm 0.02. \quad (2)$$

However, additional information is needed before the absolute masses can be determined. There exist two options to achieve this goal in double-lined DDs. From Fig. 8, it is evident that the “system velocities” derived for components 1 and 2 differ by 14.3 km/s, much more than naively expected from the error bars. However, this is easily explained by the mass dependent gravitational redshift of white dwarfs, $z = GM/(Rc^2)$.

This offers the opportunity to determine masses of the individual white dwarfs in double-lined DDs. For a given mass-radius relation (e.g. from the cooling sequences plotted in Fig. 5) gravita-

tional redshifts can be computed as a function of mass. Since the mass ratio is given by Eq. 2, only one combination of masses can fulfil both constraints. In the case of HE1414-0828 we derived individual masses $M_1 = 0.55 \pm 0.03 M_\odot$ and $M_2 = 0.71 \pm 0.03 M_\odot$. The result for HE1414-0848 did not depend much (deviations not larger than $0.01 M_\odot$) on the particular choice of a mass-radius relation. The sum of both white dwarf masses is $M = 1.26 \pm 0.06 M_\odot$. Thus HE1414-0848 is a massive DD with a total mass only 10% below the Chandrasekhar limit.

If double-lined systems contain white dwarfs of low mass and/or similar mass the gravitational redshift differences are very small and this method cannot be used to determine absolute masses. Another method, which works in these cases as well, are model atmosphere analyses of the spectra to determine the fundamental parameters effective temperature and surface gravity, $g = GM/R^2$, of the stars. Because the HE1414-0848 system is double-lined the spectra are a superposition of both individual white dwarf spectra. A direct approach would be to disentangle the observed spectra by deconvolution techniques into the spectra of the individual components. Then we could analyse the spectra by fitting synthetic spectra developed for single-lined white dwarfs to the individual line profiles. Such procedures were successfully applied to main sequence double-lined binaries. However, they have not been tested for white dwarfs, for which the wavelength shifts caused by orbital motions are much smaller than the line

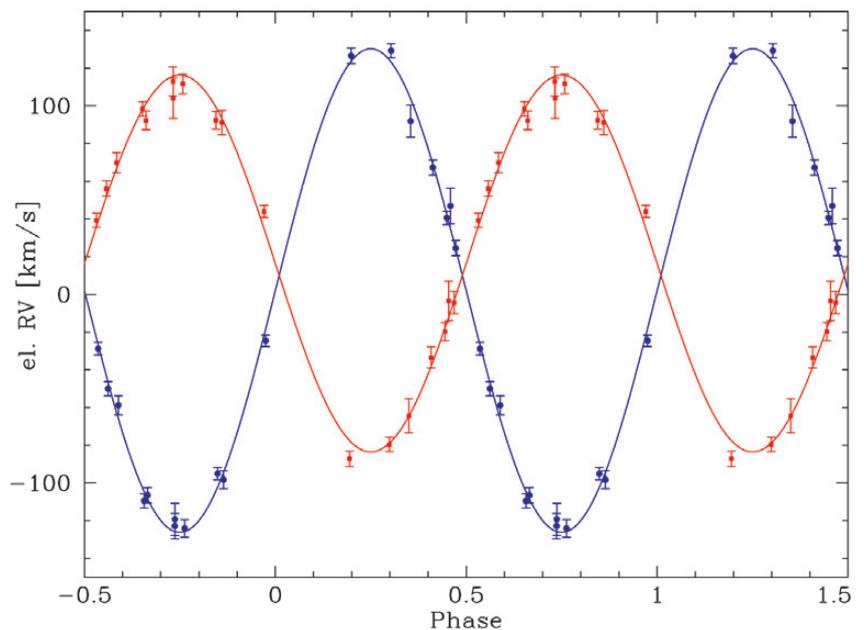


Figure 8: Measured RVs as a function of orbital phase and fitted sine curves for HE 1414-0848. Blue circles/red rectangles indicate the less/more massive component. Note the difference of the “system velocities” γ_0 between both components caused by gravitational redshift.

widths of the broad Balmer lines. Therefore we choose a different approach for our analysis of double-lined DD systems. We used the programme FITSB2, which performs a spectral analysis of both components of double-lined systems. It is based on a χ^2 minimization 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.

The total number of fit parameters (stellar and orbital) is high. Therefore we fixed as many parameters as possible before performing the model atmosphere analysis. We have kept the radial velocities of the individual components fixed according to the radial velocity curve. Since the mass ratio is already accurately determined from the radial velocity curve we fixed the gravity ratio. The remaining fit parameters are the effective temperatures of both components and the gravity of the primary. The gravity of the secondary is adjusted according to the primary value during the fitting procedure. The surface gravities also determine the relative weight of the two model spectra from the radius, obtained from mass-radius relations. The flux ratio in the V-band is calculated from the actual parameters and the model fluxes are scaled accordingly. The individual contributions are updated consistently as part of the iteration procedure.

The results for HE1414-0848 are $T_{\text{eff}}/\log g = 8380 \text{ K}/7.83$ and $10900 \text{ K}/8.14$ for components 1 and 2. A sample fit is shown in Fig. 9. The derived $\log g$ values are in good agreement with the values corresponding to the masses derived from the RV curves: $\log g = 7.92$ and 8.16 , respectively.

We have plotted HE1414-0848 as well as our other results on double-lined systems in Fig. 6. Note that one double-lined system is probably a SN Ia progenitor. However, the RV curve of the hotter component is very difficult to measure causing the large error bars. Observing time with the far-UV satellite FUSE has been allocated, which will enable us to measure more accurate RVs.

Concluding remarks

The large programme part of SPY has now been completed with some observations underway to complete the observations of the white dwarfs with only one spectrum taken during the survey. We increased the number of white dwarfs checked for RV variability from 200 to 1000 and multiplied the number of known DDs by a factor of seven (from 18 to 139) compared to the results achieved during the last 20 years. Our sample includes many short period binaries (Fig. 6), several with masses

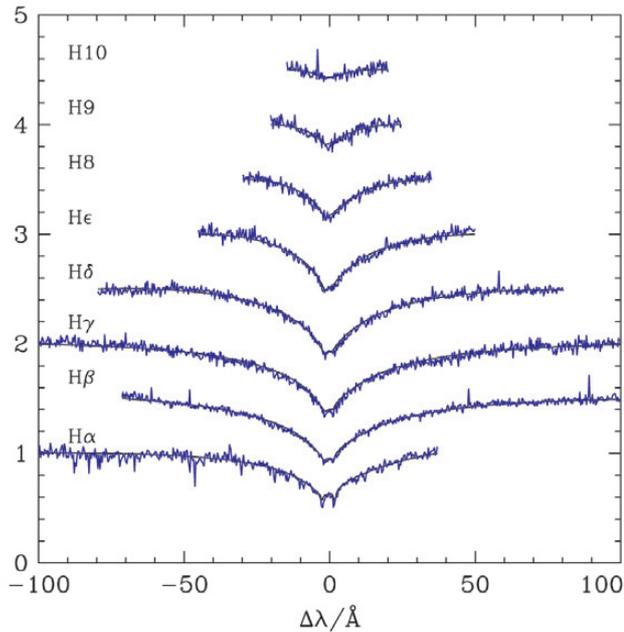


Figure 9: Model atmosphere fit of the Balmer series of HE 1414-0848 with FITSB2. This is only a sample fit. All available spectra, covering different orbital phases, were used simultaneously.

closer to the Chandrasekhar limit than any system known before, greatly improving the statistics of DDs. We expect this survey to produce a sample of about 150 DDs.

This will allow us not only to find several of the long sought potential SN Ia precursors (if they are DDs), but will also provide a census of the final binary configurations, hence 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 white dwarfs 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.

Spin-off results

SPY produces an immense, unique sample of very high resolution white dwarf spectra. This database will have a large impact on many fields of white dwarf science. It will allow us for the first

time to tackle many longstanding questions on a firm statistical basis. Among those are the mass distribution of white dwarfs, the kinematical properties of the white dwarf population, surface compositions, luminosity function, rotational velocities, and detection of weak magnetic fields. A first part of the SPY sample was published in a recent paper of Koester et al. (2001), covering observations of about 200 white dwarfs of spectral types DA and DB. For all spin-off opportunities mentioned above the statistics will be dramatically improved by the final white dwarf spectra database. We are exploiting the SPY sample for two spin-off projects, which take advantage of the high spectral resolution: the kinematics of white dwarfs (Pauli et al. 2003) and their rotational velocities. A more detailed description of ongoing spin-off activity is given in Napiwotzki et al. (2001).

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