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CLOSE BINARY WHITE DWARFS AND SUPERNOVAE IA

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RESUMEN

Informamos sobre el estado actual de los “surveys” de velocidades radiales para binarias de enanas blancas (degeneradas dobles - DDs) incluyendo SPY (Exploración ESO de progenitoras de supernovas Ia) que recientemente se llevaron a cabo en el VLT. Una amplia muestra de DDs nos permitirá poner fuertes restricciones sobre las fases evolutivas de los sistemas progenitores de binarias cercanas y también llevar a cabo pruebas observacionales del escenario DD para supernovas de tipo Ia.

ABSTRACT

We report on the current status of radial velocity surveys for white dwarf binaries (double degenerates – DDs) including SPY (ESO Supernovae Ia progenitor survey) recently carried out at the VLT. A large sample of DD will allow us to put strong constraints on the phases of close binary evolution of the progenitor systems and to perform an observational test of the DD scenario for supernovae of type Ia.

Key Words: **BINARIES: CLOSE — WHITE DWARFS**

1. 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 and these proceedings). According to the current consensus SN Ia are caused by the thermonuclear explosion of a white dwarf (WD) growing to the Chandrasekhar mass of $\approx 1.4 M_{\odot}$ in a binary system. Several channels have been identified as possibly yielding such a critical mass. They can be broadly grouped into two classes. The single degenerate (SD) channel (Whelan & Iben 1973) in which the WD is accompanied by either a main sequence star, a (super)giant, or a helium star, as mass donor and the double degenerate (DD) channel where the companion is another WD (Webbink 1984; Iben & Tutukov 1984). 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.

2. SURVEYS FOR CLOSE DD

The orbital velocity of WDs in potential SN Ia progenitor systems must be large (> 150 km/s) making radial velocity (RV) surveys of WDs the most promising detection method. Most WDs are of the hydrogen-rich spectral type DA, displaying broad hydrogen Balmer lines. The remaining WDs are of non-DA spectral types (e.g. DB and DO) and their atmospheres contain no or very little hydrogen. Accurate RV measurements are possible for DA WDs thanks to sharp cores of the Hα profiles caused by NLTE effects (cf. Fig. 1).

The first systematic search for DDs among white dwarfs was performed by Robinson & Shafter (1987), being followed a few years later by later Bragaglia et al. (1990) and Foss et al. (1991). A total of about 100 WDs was observed and only two confirmed DDs were detected. The low number of detections prompted Bragaglia et al. (1990) to state that DDs, at least those with DA components, are unlikely precursors of SN Ia. Typical accuracies for these three investigations were $40 - 50$ km/s, which is only good enough to detect systems with periods up to $\approx$12 h (if inclination angle or phase differences are not too unfavourable), but not for longer period systems. Two larger surveys were performed in the late nineties:

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one by Saffer et al. (1998) who performed observations with a modest accuracy of 25 km/s. Maxted & Marsh (1999) and Maxted et al. (2000a) did observations with quite good RV accuracy of $2-3$ km/s. Combining all the surveys about 200 WDs were checked for RV variations with sufficient accuracy yielding 18 DDs with periods $P < 6.3$ d (see Marsh 2000 for a compilation). However, none of these systems seems massive enough to qualify as an SN Ia precursor. This is not surprising, as theoretical simulations suggests 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.

Recently, subdwarf B (sdB) stars with WD components have been proposed as potential SNe Ia progenitors by Maxted et al. (2000b), who announced the serendipitous discovery of a massive WD companion of the sdB KPD 1930+2752. If the canonical sdB mass of $0.5 M_\odot$ is adopted, the mass function yields a minimum total mass of the system in excess of the Chandrasekhar limit. Since this system will merge in less than a Hubble time, this makes KPD 1930+2752 a SN Ia progenitor candidate (although this interpretation has been questioned by Ergma et al. 2001).

Note that some very short period DDs reside in interacting binaries of the AM CVn class (cf. Woudt & Warner 2003 for a catalogue). Three recently detected systems have periods between five and ten minutes. More detailed discussions can be found in other contributions of these proceedings.

3. THE SPY PROJECT

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 WDs. This situation changed after the ESO VLT became available. 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. Note that SPY is the first RV survey which performs a systematic investigation of both classes of WDs, the DAs and non-DAs. The use of several helium lines enables us to reach an accuracy similar to the DA case. A detailed description of the SPY project can be found in Napiwotzki et al. (2001a).

The large programme has finished at the end of March 2003. A total of 1014 stars were observed. This corresponds to 75% of the known WDs accessible by VLT and brighter than $B = 16.5$. At this time a second spectrum was still lacking for 242 WDs, but observing time has been granted to complete these observations. Currently we could check 875 stars for RV variations, and detected ≈100 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 (cf. below). Our sample includes many short period binaries (some examples are discussed in Sect. 3), several with masses closer to the Chandrasekhar limit than any system known before, including one possible SN Ia progenitor candidate (cf. Fig. 3). 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. 1.

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. 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 the late stages of their evolution.

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. A lower limit on the secondary mass can be derived for $i = 90°$. For a statistical analysis it is useful to adopt the most probable inclination $i = 52°$. We

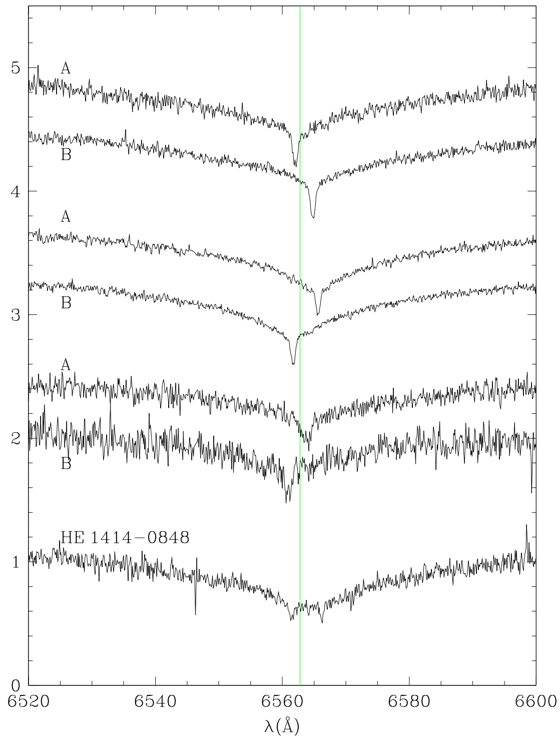

Fig. 1. Three single-lined RV variable DDs from our VLT survey and the double-lined binary HE 1414−0848. The vertical line marks the rest wavelength of Hα. The spectra are slightly rebinned (0.1 Å) without degrading the resolution.

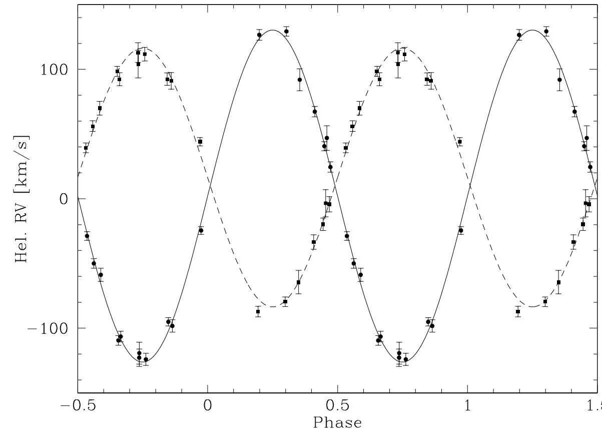

Fig. 2. Measured RVs as a function of orbital phase and fitted sine curves for HE 1414-0848. Circles and solid line/rectangles and dashed line indicate the less/more massive component 1/2. Note the difference of the "systemic velocities" γ_0 between both components caused by gravitational redshift.

have plotted the single-lined systems with the resulting system mass in Fig. 3. 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.

Sometimes spectral features of both DD components are visible (Fig. 1), i.e. these are double-lined spectroscopic binaries (SB2). As an example for other double-lined systems we discuss here the DA+DA system HE 1414−0848 (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 WDs can be measured, and the orbits of both individual components can be determined (Fig. 2). For our example HE 1414−0848 we derived a period of $P = 12^{\mathrm{h}}25^{\mathrm{m}}44^{\mathrm{s}}$. The ratio of velocity amplitudes is directly related to the mass ratio of both components: $M_2/M_1 = K_1/K_2 = 1.28 \pm 0.02$. 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. 2 it is evident that the "system velocities" derived for components 1 and 2 differ by 14.3 km/s, which results from the mass dependent gravitational redshift of WDs $z = GM/Rc^2$. This offers the opportunity to determine masses of the individual WDs in double-lined DDs. 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. In the case of HE 1414−0828 we derived individual masses $M_1 = 0.55 \pm 0.03 M_\odot$ and $M_2 = 0.71 \pm 0.03 M_\odot$. The sum of both WD masses is $M = 1.26 \pm 0.06 M_\odot$. Thus HE 1414−0848 is a massive DD with a total mass only 10% below the Chandrasekhar limit.

This method cannot be used if the systems consist of WDs of low mass, for which the individual gravitational redshifts are small, or if their masses are too similar, because the resulting redshift differences are too small. 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 this system is double-lined the spectra are a superposition of both individual WD spectra. Our approach to this problem consists of a fit of all available spectra covering different spectral phases simultaneously with a newly developed program FITSB2, which allows the determination of the individual stellar parameters. As a test of this procedure we analysed the DD HE 1414−0848 discussed above. The results are $T_{\mathrm{eff}}/\log g = 8380\,\mathrm{K}/7.83$ and $10900\,\mathrm{K}/8.14$ for

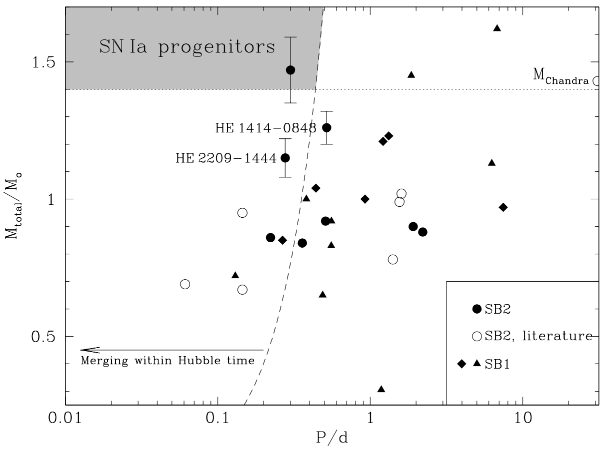

Fig. 3. Periods (P) and system masses ($M_{\rm total}$) determined from follow-up observations of DDs from SPY. Results for double-lined systems are compared to previously known systems. The other DD systems are single-lined (triangles: WD primaries; diamonds: sdB primaries). The masses of the unseen companions are estimated from the mass function for the expected average inclination angle ($i = 52°$).

components 1 and 2. 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.

4. CONCLUDING REMARKS

The large programme part of SPY has now been completed with some observations underway to complete the observations of the WDs with only one spectrum taken during the survey. We increased the number of WDs checked for RV variability from 200 to 1000 and multiplied the number of known DDs by more than a factor of six (from 18 to $\approx$120) compared to the results achieved during the last 20 years. Our sample includes many short period binaries (Fig. 3), several with masses closer to the Chandrasekhar limit than any system known before, greatly improving the statistics of DDs. 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. More individual objects are discussed in Napiwotzki et al. (2001b) and Karl et al. (2003).

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. 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, the existence of three short period systems with masses close to the Chandrasekhar limit, which will merge within 4 Gyrs to two Hubble times 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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