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Letter to the Editor

Binaries discovered by the SPY project

I. HE 1047–0436: A subdwarf B + white dwarf system[⋆,⋆⋆]

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Abstract. In the course of our search for double degenerate binaries as potential progenitors of type Ia supernovae with the UVES spectrograph at the ESO VLT (ESO **S**N Ia **P**rogenitor surve**Y** – SPY) we discovered that the sdB star HE 1047−0436 is radial velocity variable. The orbital period of 1.213253 d, a semi-amplitude of 94 km s^{-1}, and a minimum mass of the invisible companion of 0.44 $M_\odot$ are derived from the analysis of the radial velocity curve. We use an upper limit on the projected rotational velocity of the sdB star to constrain the system inclination and the companion mass to $M > 0.71\,M_\odot$, bringing the total mass of the system closer to the Chandrasekhar limit. However, the system will merge due to loss of angular momentum via gravitational wave radiation only after several Hubble times. Atmospheric parameters and metal abundances are also derived. The resulting values are typical for sdB stars.

Key words. stars: early-type – binaries: spectroscopic – stars: fundamental parameters – white dwarfs

1. Introduction

Type Ia supernovae (SNe Ia) play a prominent role in the study of cosmic evolution. In particular they are regarded as one of the best standard candles to determine the cosmological parameters H_0, Ω and Λ (e.g. Riess et al. 1998; Leibundgut 2001). What kind of stars produce SN Ia events remains largely a mystery (e.g. Livio 2000). There is general consensus that the event is due to the thermonuclear explosion of a white dwarf (WD) when a critical mass is reached, but the nature of the progenitor system remains unclear.

One of the two viable scenarios is the so-called double degenerate (DD) scenario (Iben & Tutukov 1984). The DD model considers a binary with the sum of the masses of the WD components larger than the Chandrasekhar mass, which merges in less than a Hubble time due the loss of angular momentum via gravitational wave radiation. Previous radial velocity (RV) surveys have discovered about 15 DDs with $P < 6\overset{\mathrm{d}}{.}3$ (see Marsh 2000). None of these systems seems massive enough to qualify as a SN Ia precursor. In order to perform a definite test of the DD scenario we have embarked on a large spectroscopic survey of 1500 WDs using the UVES spectrograph at the ESO VLT UT2 (Kueyen) to search for RV variable WDs and pre-WDs (ESO **S**N Ia **P**rogenitor surve**Y** – SPY).

Recently, subluminous B stars (sdB) with WD companions have been proposed as potential SNe Ia progenitors by Maxted et al. (2000) who discovered that KPD 1930+2752 is a sdB+WD system. Its total mass exceeds the critical mass and the components will merge within a Hubble time which makes KPD 1930+2752 the best candidate for a SN Ia progenitor known today (although this interpretation has been questioned recently, Ergma et al. 2001).

SdB stars are pre-white dwarfs of low mass (≈0.5 $M_\odot$) still burning helium in the core, which will evolve directly to the WD stage omitting a second red giant phase (Heber 1986). Only seven sdB+WD systems with known periods are available in the literature. Except for KPD 1930+2752 their total masses do not exceed the Chandrasekhar limit.

Here we report on follow-up spectroscopy of HE 1047−0436 (Sect. 2). The RV curve is derived and the nature of the companion is discussed in Sect. 3. A spectroscopic analysis and further constraints on the system inclination and companion mass are presented in Sect. 4.

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⋆ Based on data obtained at the Paranal Observatory of the European Southern Observatory for program Nos. 165.H-0588 and 266.D-5658.

⋆⋆ Based on observations collected at the German-Spanish Astronomical Center (DSAZ), Calar Alto, operated by the Max-Planck-Institut für Astronomie Heidelberg jointly with the Spanish National Commission for Astronomy.

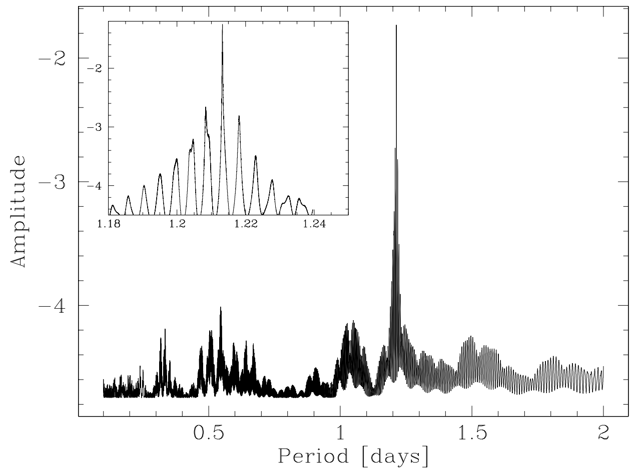

Fig. 1. Power spectrum of the HE 1047−0436 measurements. The inset shows details of the region around the main peak.

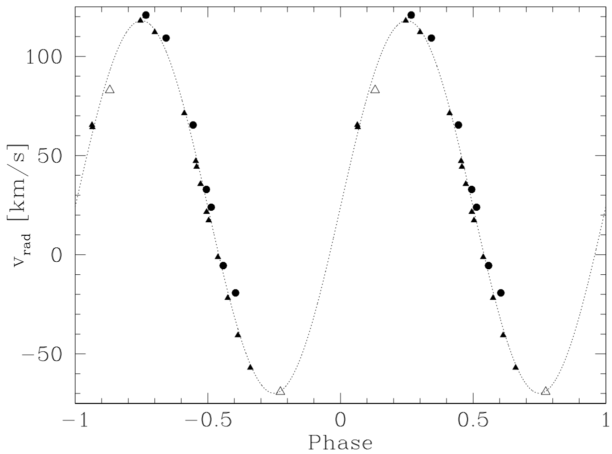

Fig. 2. Measured *RV*s as a function of orbital phase and fitted sine curve for HE 1047−0436. Filled triangles indicate 2001 UVES observations, open triangles both 2000 UVES discovery observations, and filled circles 2001 TWIN measurements.

2. Observations and data analysis

HE 1047−0436 ($\alpha_{2000} = 10^{\rm h}50^{\rm m}26\overset{\rm s}{.}9$, $\delta_{2000} = -4°52'36''$, $B_{\rm pg} = 14\overset{\rm m}{.}7$) was discovered by the Hamburg ESO survey (HES; Wisotzki et al. 1996; Christlieb et al. 2001) as a potential hot WD and, therefore, was included in our survey. The UVES spectra showed that it is in fact a sdB star (Christlieb et al. 2001) and a rather large *RV* shift of 160 km s^{-1} was found which made the star a prime target for further study.

14 high resolution Echelle spectra of HE1047-0436 have been secured with VLT-UVES between March 7 and 18, 2001. The nominal resolution with the 2.1″ slit used by us amounts to $\frac{\lambda}{\delta\lambda} = 19\,000$. Additional long slit spectra of somewhat lower resolution (1 Å) have been obtained at the Calar Alto observatory using the TWIN spectrograph on March 11 and 12, 2001. Details on the observational set up of the UVES instrument and the data reduction can be found in Koester et al. (2001). The TWIN instrument and the reduction strategy are described in Napiwotzki & Schönberner (1995).

3. Radial velocity curve and the nature of the invisible companion

Radial velocities from all UVES and TWIN spectra were derived by cross correlating parts of the blue spectra that display numerous sharp metal absorption lines besides helium and Balmer lines to a synthetic spectrum calculated from an LTE model atmosphere (see below). The measurements are accurate to ±3 km s^{-1} for the UVES data and somewhat less precise (±12 km s^{-1}) for the TWIN data because of the lower spectral resolution of the latter instrument.

Since this system is single-lined the analysis is straightforward. A periodogram analysis was performed and the resulting power spectrum is shown in Fig. 1 and the best fit *RV* curve in Fig. 2. The discovery spectra taken at April 21 and May 17, 2000 are included in Figs. 1 and 2. Since these spectra were taken about one year before the 2001 data a very accurate period could be determined: $P = 29^{\rm h}7^{\rm m}5^{\rm s}$ and a semi-amplitude of 94 km s^{-1}. The system velocity is $\gamma_0 = 25$ km s^{-1} (this has to be corrected by a gravitational redshift of 1.9 km s^{-1} to derive the real system velocity). Accordingly the ephemeris for the time T_0 defined as the conjunction time at which the star moves from the blue side to the red side of the *RV* curve (cf. Fig. 2) is

$$\text{Hel.JD}(T_0) = 244\,51975.03228 + 1.213253 \times E.$$

Two aliases exist, which differ by $\pm 6^{\rm m}$, but they can be ruled out on a high confidence level (cf. inset of Fig. 1).

Since HE 1047−0436 is a single-lined binary we can only use the mass function to constrain the mass of the invisible companion. From a comparison with evolutionary calculations (Dorman et al. 1993) we adopted $M = 0.474\,M_\odot$ for the sdB primary. The mass function yields a lower limit of $0.44\,M_\odot$ for the invisible companion (for an inclination $i = 90°$). Therefore we conclude that it is a WD with a C/O core. A main sequence companion with such a high mass can be ruled out, because it would leave a detectable fingerprint in our high-resolution spectra. In the next section we will show how the measurement of the projected rotational velocity of the sdB constrains the inclination i and the WD mass.

4. Spectroscopic analysis

The stars in the HE 1047−0436 binary are only separated by ≈5 $R_\odot$ (slightly depending on i). Thus the system must have gone through phases of heavy interaction, probably common envelope evolution, during the red giant stages of the progenitors. Thus we checked if the sdB parameters and chemical abundances deviate from normal sdBs.

In order to improve the *S*/*N* ratio the UVES spectra were *RV* corrected and then coadded. The coadded as well as the individual UVES and spectra TWIN have been analyzed to derive atmospheric parameters using

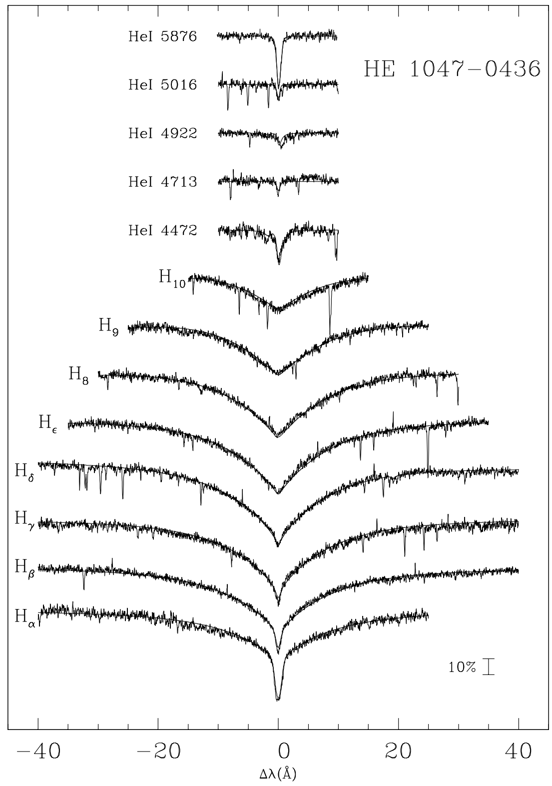

Fig. 3. Fit of the hydrogen and helium lines of the coadded spectrum of HE 1047−0436.

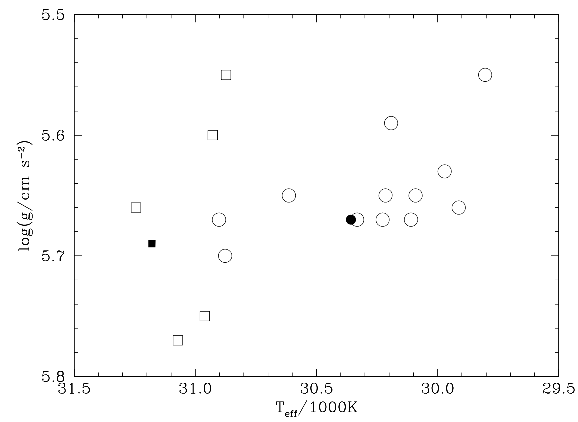

Fig. 4. Parameters derived from individual UVES and TWIN spectra (open circles and squares) and the coadded spectra (filled symbols).

NLTE model atmospheres (Napiwotzki 1997) and a χ^2 procedure described by Napiwotzki et al. (1999). An LTE metal abundance analysis of the coadded UVES spectrum was performed (see Heber et al. 2000 for details of the models and the fit procedure).

Matching the synthetic Balmer and He I line profiles to the observations resulted in effective temperature, gravity and He abundance with very small fitting errors, i.e. $T_{\rm eff} = 30242 \pm 39\,{\rm K}$; $\log g = 5.66 \pm 0.008$ and $\log \frac{n_{\rm He}}{n_{\rm H}} = -2.632 \pm 0.026$ (Fig. 3). Adopting the sdB mass of $0.47\,M_\odot$ the radius can be calculated from the gravity: $R = 0.17 \pm 0.02\,R_\odot$.

Table 1. Metal abundances for HE 1047−0436 compared to Feige 36 (Edelmann et al. 1999) and to solar composition (Grevesse & Sauval 1998). n is the number of spectral lines per ion.

ion	n	ϵ(HE 1047−0436)	ϵ(Feige 36)	ϵ(sun)
C II	4	8.03 ± 0.12		8.52
C III	3	7.94 ± 0.11	7.18 ± 0.20	
N II	49	8.01 ± 0.19	7.67 ± 0.12	7.92
N III	1	8.40		
O II	23	7.80 ± 0.11	7.94 ± 0.17	8.83
Mg II	1	6.78	6.58	7.58
Al III	3	5.60 ± 0.03	5.75 ± 0.06	6.47
Si III	7	6.82 ± 0.23	6.93 ± 0.18	7.55
Si IV	1	6.60		
S II	14	7.57 ± 0.23	7.71 ± 0.43	7.33
S III	11	7.48 ± 0.33	7.34 ± 0.47	
Ar II	7	7.17 ± 0.22	7.09 ± 0.10	6.40
Fe III		<6.8	7.20 ± 0.26	7.50

Since more than a dozen individual UVES spectra are available systematic errors can be estimated. Individual results (with one exception) differ by no more than ±500 K and ±0.05 dex in $\log g$ from that derived from the coadded spectrum (see Fig. 4). Another important accuracy check can be obtained from the long slit spectra. The fit of the coadded TWIN spectrum resulted in a moderately higher effective temperature (about 1000 K) than from the UVES spectrum, whereas the gravity is in very close agreement (cf. Fig. 4).

Lines of several heavy elements can be identified in the UVES spectra (cf. Table 1). The large number of N II lines allows to determine the microturbulent velocity which turns out to be zero. The resulting abundances are summarized in Table 1 and compared to the sdB star Feige 36 (Edelmann et al. 1999) which has atmospheric parameters ($T_{\rm eff} = 29\,700\,{\rm K}$, $\log g = 5.9$, $\log \frac{n_{\rm He}}{n_{\rm H}} = -2.1$) very similar to HE 1047−0436 and to solar composition. In order to match the ionization equilibria of C, N, Si, and S it would be necessary to lower $T_{\rm eff}$ to 29 000 K. This is probably caused by the neglect of NLTE effects. However, the abundances are almost unaltered (by less than 0.1 dex) by such a change in $T_{\rm eff}$.

The comparison of the metal abundances of HE 1047−0436 and Feige 36 in Table 1 shows that the abundance patterns are quite similar. Only iron is somewhat underabundant in HE 1047−0436 (only an upper limit could be derived). We conclude that the phases of close binary interaction didn't produce any detectable peculiarities of the sdB star.

A closer inspection of the metal lines showed that these are much narrower than expected from the nominal resolution ($R \approx 19\,000$). The obvious reason is that the seeing during all exposures ($0.4'' \ldots 1.2''$) was smaller than the slit width ($2.1''$). This enables us to derive meaningful upper limits on the projected rotational velocity $v \sin i$ of the sdB. Since we were interested in minimizing the instrumental broadening we coadded only the seven spectra taken during periods of best seeing ($0.4'' \ldots 0.8''$) for this

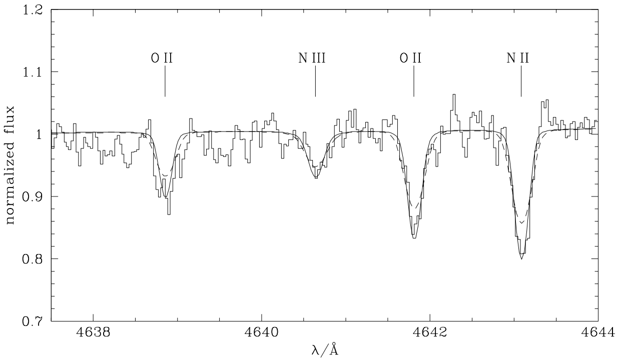

Fig. 5. Observed spectrum (coaddition of the seven spectra obtained during best seeing) compared to synthetic spectra with $v \sin i = 0$ (solid line) and $v \sin i = 10\,\mathrm{km\,s^{-1}}$ (dashed line).

task. We adopted a conservative value of the spectral resolution corresponding to the mean of the three best seeing values (0.5″).

Following the procedure described in Heber et al. (1997) we took synthetic line profiles, convolved them with rotational profiles, and measured the fit quality (Fig. 5). We limited this to lines of the ions N II and O II because for these the quality of the atomic data is highest and these lines are best reproduced by the model spectrum calculated with the abundances of Table 1. A 3σ upper limit on $v \sin i$ of $4.7\,\mathrm{km\,s^{-1}}$ results.

Since the synchronization time between orbit and rotation of the sdB is less than 700 000 years (Tassoul & Tassoul 1992), it is very likely that orbital and rotational period are equal. This corresponds to a rotational velocity of the sdB of $7.2 \pm 0.8\,\mathrm{km\,s^{-1}}$. Our upper limit on $v \sin i$ thus transforms to an upper limit on the inclination angle of this system of 48°. From the mass function we then derive a lower limit on the mass of the invisible companion of $0.71\,M_\odot$. Thus the total mass of the binary is $1.2\,M_\odot$ or even larger, close to the Chandrasekhar limit. A more definite determination would need dedicated observations with a narrow slit and a well defined spectral resolution.

5. Discussion and conclusions

We measured accurate RVs for the sdB star He 1047−0436 from high resolution spectra and derived an orbital period of 1.213253 d and a semi-amplitude of $94\,\mathrm{km\,s^{-1}}$. The mass of the invisible companion is shown to be at least $0.44\,M_\odot$ indicating that the companion is likely a C/O core WD. If we make the reasonable assumption, that the sdB rotation is synchronized with the orbital period, we can use an upper limit on $v \sin i$ to compute an upper limit on the inclination angle and a lower limit on the WD mass of $0.71\,M_\odot$. Six of the seven known sdB+WD binaries (Maxted et al. 2001) have considerably shorter periods (0.09 d to 0.57 d) than HE 1047−0436. Only PG 1538+269 has a longer orbital period (2.501 d, Saffer et al. 1998). Even the minimum mass we derive for the WD companion ranks third among the known systems.

From a quantitative spectral analysis precise atmospheric parameters and metal abundances were derived. Intercomparison with an analysis of long slit spectra demonstrated that the atmospheric parameters derived from the Echelle spectra are highly reliable and systematic errors are small. The resulting atmospheric parameters and metal abundances are typical for sdB stars.

The effective temperature of HE 1047−0436 lies within the range where short period (2–10 min) non-radial pulsating sdB stars were discovered (O'Donoghue et al. 1999). Photometric monitoring of HE 1047−0436 for about 20 min did not reveal any variations above a level of 2 mmag (Østensen, priv. com.)

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