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Revealing the True Nature of Hen 2-428

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Abstract: The nucleus of Hen 2-428 is a short orbital period (4.2 h) spectroscopic binary, whose status as potential supernovae type Ia progenitor has raised some controversy in the literature. We present preliminary results of a thorough analysis of this interesting system, which combines quantitative non-local thermodynamic (non-LTE) equilibrium spectral modelling, radial velocity analysis, multi-band light curve fitting, and state-of-the art stellar evolutionary calculations. Importantly, we find that the dynamical system mass that is derived by using all available He II lines does not exceed the Chandrasekhar mass limit. Furthermore, the individual masses of the two central stars are too small to lead to an SN Ia in case of a dynamical explosion during the merger process.

Keywords: binaries: spectroscopic; stars: atmospheres; stars: abundances; supernovae

1. Introduction

The detection and study of progenitor systems of type Ia supernovae (SN Ia) are crucial to understand the exact explosion mechanism of these important cosmic distance indicators. Although there is a general consensus that only the thermonuclear explosion of a white dwarf can explain the observed features of those events, the nature of their progenitor systems still remains elusive. In the single-degenerate model, a white dwarf accretes material from a non-degenerate companion and explodes when it reaches the Chandrasekhar mass limit [1]. An alternative scenario is the double-degenerate model, in which the explosion is triggered during the merger process of two white dwarfs [2–4]. Identifying progenitors for the latter scenario is particularly interesting in view of the applicability of SN Ia as standardisable candles, as the merging system could exceed or fall below the Chandrasekhar limit significantly.

Santander-Garcia et al. [5] have claimed to have discovered the first definite double-degenerate, super-Chandrasekhar system that will merge within a Hubble time, namely the central stars of the planetary nebula (CSPN) Hen 2-428. They found a photometric period of 4.2 h and that He II λ 5411 Å is double lined and time variable. By fitting the radial velocities (RVs) and light curves, they concluded that the system consists of two pre-white dwarfs with equal masses of 0.88 $M_\odot$. In this case, the system would merge within 700 million years making, Hen 2-428 one of the best SN Ia progenitor candidates known.

This scenario has since been challenged by Garcia-Berro et al. [6], who criticized the strong mismatch between the luminosities and radii of both pre-white dwarf components as derived by [5] with the predictions from stellar evolution models [7]. In addition, Reference [6] suggested that the variable He II $\lambda\,5411$ Å line might instead be a superposition of an absorption line plus an emission line, possibly arising from the nebula, the irradiated photosphere of a close companion, or a stellar wind. Since this would question the dynamical masses derived by [5], Reference [6] that repeated the light curve fitting and showed that the light curves of Hen 2-428 may also be fitted well by assuming an over-contact binary system that consists of two lower mass (i.e., masses of 0.47 $M_\odot$ and 0.48 $M_\odot$) stars. Thus, Reference [6] concludes that the claim that Hen 2-428 provides observational evidence for the double degenerate scenario for SN Ia is premature.

Given the potential importance of Hen 2-428 as a unique laboratory to study the double degenerate merger scenario, it is highly desirable to resolve this debate. Therefore, we use an improved approach for the analysis of this unique object by combining quantitative non-LTE spectral modelling, RV analysis, multi-band light curve fitting, and state-of-the art stellar evolutionary calculations.

2. Spectral Analysis

Our spectral analysis is based on the Very Large Telescope/FOcal Reducer and low dispersion Spectrograph 2 (VLT/FORS2) and Gran Telescopio Canarias/Optical System for Imaging and low-Intermediate-Resolution Integrated Spectroscopy (GTC/OSIRIS) spectra. FORS2 spectra were downloaded from the European Southern Observatory (ESO) archive (ProgIDs 085.D-0629(A), 089.D-0453(A)) and by reduced by using standard IRAF procedures. Calibrated GTC/OSIRIS spectra were obtained from the GTC PublicArchive (ProgID GTC41-13A). Since the relatively broad and deep absorption lines in the spectra of Hen 2-428 cannot be fitted assuming a single component, we conclude that Hen 2-428 is indeed a double lined spectroscopic binary. We employed the Tübingen Model Atmospheres Package (TMAP, [8–10]) to produce state-of-the-art non-LTE model atmospheres. Initially, our models contain only H and He. The model grid spans from T_eff = 30.0–70.0 kK (2.5 kK steps), $\log g$ = 4.25–6.00 (0.25 steps), and covers three He abundances ($\log(\mathrm{He/H}) = -2, -1, 0$, number fractions). The first results of this analysis based on the FORS2 spectra only were presented in [11]. We extended this analysis by fitting the OSIRIS spectra and considering a variable flux contribution of the two stars in our fitting procedure. To constrain the parameters of the system, we used the XSPEC software [12,13], a χ^2 minimisation code, originally designed for X-ray spectra, but which has been adapted to work on optical data [14]. XSPEC determines the best fit model for the input parameters, which in our case are the effective temperatures (T_eff), surface gravities ($\log g[\mathrm{cm/s^2}]$), He abundances, RVs, and the flux contribution of each star. First, the radial velocity of each component was found, and then these were fixed whilst deriving T_eff, $\log g$, $\log(\mathrm{He/H})$, and the flux contribution of each star simultaneously. For the first star, we find $T_\mathrm{eff} = 48 \pm 7$ kK, $\log g = 5.00 \pm 0.1$, $\log(\mathrm{He/H}) = -1.1$ and relative flux contribution of 46%. For the second star, we derive $T_\mathrm{eff} = 46 \pm 7$ kK, $\log g = 4.8 \pm 0.1$, $\log(\mathrm{He/H}) = -1.0$ and relative flux contribution of 54%. The reduced χ^2 value for these parameter is 1.04. In Figure 1, we show the best fit model (red) compared to an OSIRIS spectrum (grey). We obtain a good fit for He II $\lambda\lambda\,4200, 4542, 5412$ Å, and also the absorption wings of the He I and H I lines are reproduced nicely. The line cores of He II $\lambda\,4686$ Å, however, appear too deep compared to the observation. This is a known problem when fitting the spectra of CSPNe and other hot stars with pure HHe models only. It has been shown that He II $\lambda\,4686$ Å is particularly susceptible to metal line blanketing [15,16]. We expect the systematic effects introduced by neglecting metal-line blanketing effects to be of the order of 0.1 dex on $\log g$ and 1 kK on T_eff [17], but we will include metals in our models for future analysis of this system to overcome this problem.

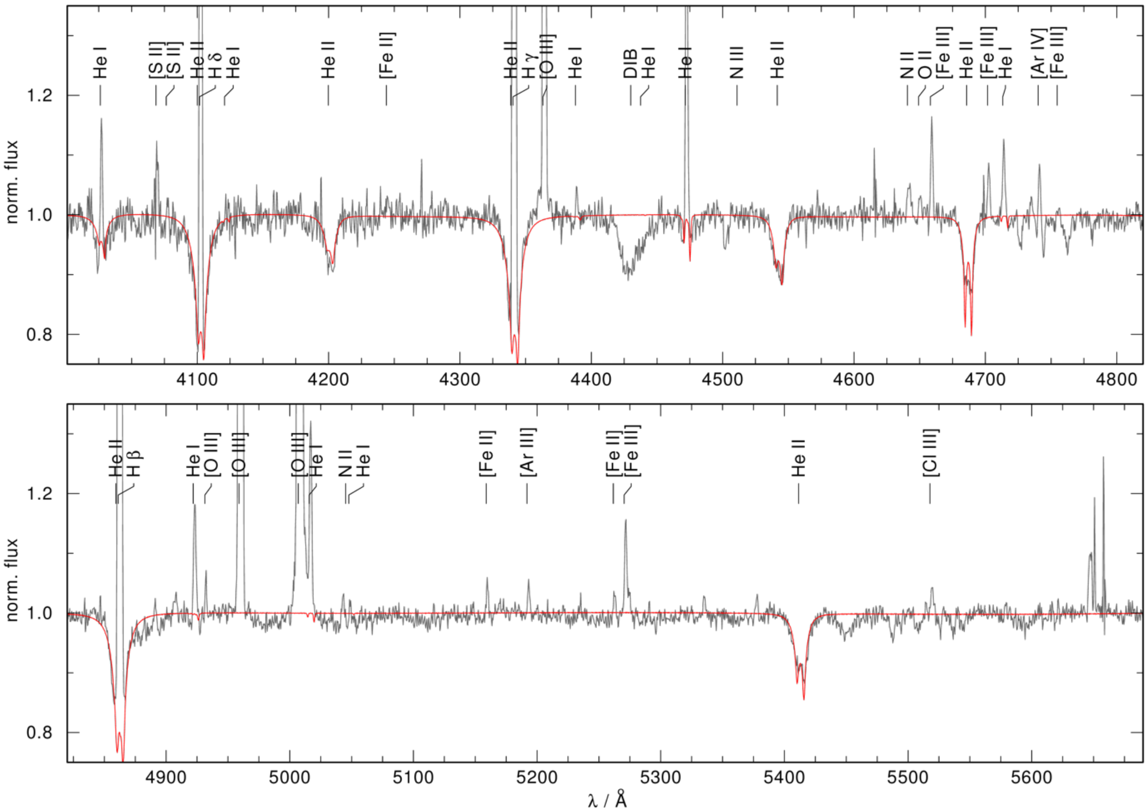

Figure 1. The best fit TMAP model (**red**) plotted against the OSIRIS spectrum (**grey**). Identified photospheric absorption lines, a diffuse interstellar band, and nebular emission lines are marked.

3. Light Curve Modelling

The analysis of the light curves (downloaded from [5]) was carried out simultaneously in B and i filter. For the analysis, we used MORO (Modified Roche Program, see [18]), which is based on the Wilson–Devinney code but is using a modified Roche model considering the influence of the radiation pressure on the shape of the stars. Due to the significant degeneracies in the parameters found in the analysis of the light curve, which result from not many independent parameters being used in the light curve analysis, we fixed the mass ratio of the system to the mass ratio, which was derived by the analysis of the radial velocity curve. Moreover, we used the temperatures derived by the spectral analysis as starting values. Initial attempts to reproduce the light curves with a contact system failed. The shape of the light curve could not be reproduced. Therefore, we tried to fit an over-contact system, which is assuming equal Roche potentials for both stars. We also considered a third light source since Hen 2-428 is known to exhibit a red-excess, which possibly results from the PN and a distant companion [19]. By varying the inclination, temperatures, Roche potentials, and luminosity ratio of both stars, the light curves could be reproduced nicely. Our preliminary best fit to the light curves is shown in Figure 2. We get a relative luminosity for the primary of 53.8% in B and 53.5% in i. We derived an additional constant flux component of 4.3% in B and 10.3% in i. We note that our fit reproduces the light curves better than the one of [6], and also slightly better than the model of [5].

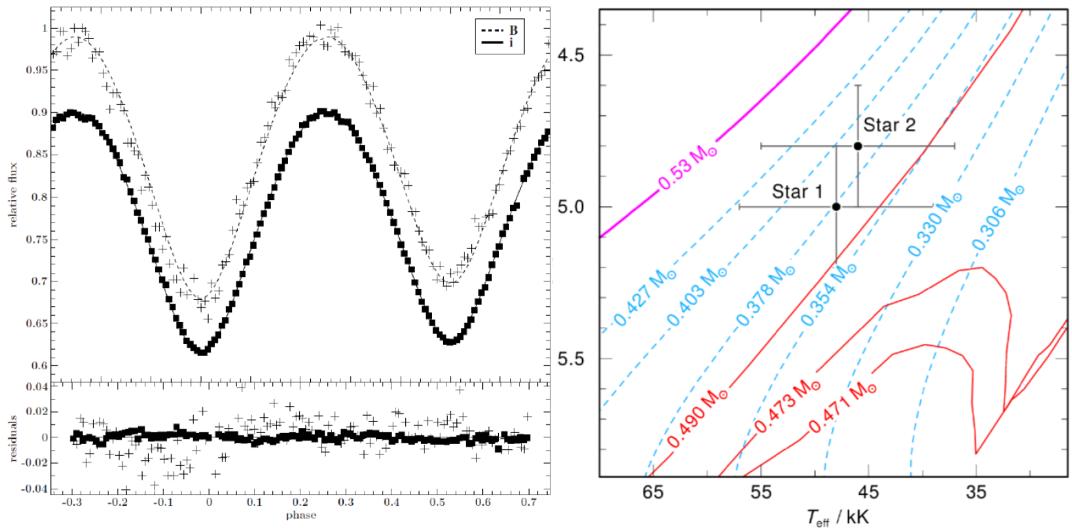

Figure 2. (**left**): Johnson B-band (dotted line) and Sloan i-band (solid line) light curves and LCURVE models; (**right**): the location of the two CSPNe of Hen 2-428 (black dots) in the $T_{\rm eff}$ -log g plane compared with a H-rich post-AGB evolutionary track (pink, [20]), post-RGB tracks (dashed blue, [21]), and post-EHB tracks (red, [22]). The tracks are labelled with stellar masses.

4. Dynamical Masses

The amplitudes of the RV curves (K_1, K_2) were obtained by sinusoidal fitting of the individual RV measurements obtained from the OSIRIS spectra of both components of the binary. This was done separately in fine steps over a range of test periods within the uncertainties of the orbital period (0.1758 ± 0.0005 d) derived from photometry by [5]. For each period, the χ^2 of the best fitting sine curve was determined and the solution with the lowest χ^2 was chosen. We can reproduce the results of [5] using their RVs as derived by merely Gaussian fitting of the He II λ 5412 Å absorption lines (fifth column in Table 1). Somewhat lower RV amplitudes are obtained when using our RVs as measured with XSPEC from our synthetic spectra for He II λ 5412 Å (forth column). Surprisingly, we find lower RV amplitudes when using only the RVs from He II λ 4686 Å (third column), and when all four He II lines were fitted simultaneously (first and second column). Since the inclination of the system ($i = 65.3 \pm 0.1$) can be constrained well from the light curve fitting, the dynamical masses of the two stars (bottom two rows in Table 1) can be calculated via the binary mass function. Importantly, we find that the combined dynamical mass obtained using all four He II lines is considerably lower than the one reported by [5] and does not exceed the Chandrasekhar mass limit.

Table 1. Dynamical and spectroscopic masses as derived in this work and by SG + 2015 [5].

	All Lines Syn. Spectra	He II λ 4686 Å Syn. Spectra	He II λ 5412 Å Syn. Spectra	He II λ 5412 Å Gaussians	SG + 2015 Gaussians
K_1 [km/s]	174 ± 16	171 ± 18	196 ± 19	203 ± 13	206 ± 8
K_2 [km/s]	174 ± 8	170 ± 10	191 ± 13	202 ± 12	206 ± 12
M_1 [$M_\odot$]	0.51 ± 0.15	0.48 ± 0.16	0.70 ± 0.23	0.81 ± 0.25	0.88 ± 0.13
M_2 [$M_\odot$]	0.51 ± 0.14	0.48 ± 0.15	0.71 ± 0.22	0.81 ± 0.24	0.88 ± 0.13

5. Discussion

Our spectral analysis is hindered by the limited number of unblended photospheric lines and the occurrences of metal line blanketing effects. Higher S/N spectra that cover other unblended photospheric lines as well as models that also include metal opacities would allow us to reduce the errors on the atmospheric parameters of the stars. Our effective temperatures are significantly larger than the ones reported by [5], who derived the stellar temperatures from light curve fitting. The narrow temperature range (30–40 kK) adopted by [5], however, is not valid as already pointed out by [6]. Ref. [5] established the upper limit of 40 kK based on the absence He II emission lines, but there are many CSPNe with even higher $T_{\rm eff}$ and also a lacking He II nebular lines. Our light curve analysis shows that the light curves can be fitted equally well with higher $T_{\rm eff}$ values compared to the ones derived by [5]. This suggests that, because of the light curve solution degeneracy, light curve modelling alone is not sufficient to derive the temperatures of the stars. Furthermore, our light curve modelling supports the idea that Hen 2-428 is an over-contact system, i.e., that both stars still share a common envelope. Therefore, should the PN be the result of the common envelope ejection, future studies of this system could reveal important insights on the common envelope ejection efficiency.

The dynamical masses are the main key to revealing the nature of Hen 2-428, i.e., to find out about the nature of the progenitor stars as well as its SNIa status. We found that the system masses vary depending on which He II lines were used, but agree within the error limits. Importantly, we find that the combined dynamical mass obtained using all four He II lines does not exceed the Chandrasekhar mass limit and that the individual masses of the two CSPNe are too small for a reasonable production of ^{56}Ni (which determines the explosion brightness) in case of a dynamical explosion during the merger process. Thus, the merging event of Hen 2-428 would not be identified as a SN Ia (see Figure 3 in [3]).

The reason why the analysis of the He II λ 5412 Å leads to a higher measurement of the RV amplitudes is unclear at the moment. Reference [19] reported an excess that shows up red-wards of 5000 Å, possibly originating from a late type companion. We speculate that this red-excess might impact the He II λ 5412 Å, but not the other three He II lines detected. Spectra extending toward longer wavelengths would help investigate the red excess further.

The lower system mass solution is also supported in view of the evolutionary time scales. The low surface gravities of both stars indicate that neither of the two stars has entered the white dwarf cooling sequence yet. The heating rate of post-asymptotic giant branch (AGB) stars is strongly mass dependent. For post-AGB stars with masses greater than about 0.7 $M_\odot$, the blue-ward evolution in the HRD is predicted to be so rapid that changes of $T_{\rm eff}$ would become noticeable within a human life span. Recent evolutionary models [20] predict that, for a 0.71 $M_\odot$ post-AGB star, it takes only 20 years to heat up from 30 kK (that is when the nebula becomes visible) to 50 kK (approximately the $T_{\rm eff}$ of both stars now). Since Hen 2-428 has been known for more than 50 years [23], this provides further evidence that the two CSPNe cannot both be such massive post-AGB stars. We also note that, if the two stars were in thermal non-equilibrium after the common-envelope was ejected, an even faster evolution would be predicted.

The spectroscopic masses of the two stars (Figure 2) agree with the dynamical masses from all four He II lines. We stress, however, that the spectroscopic masses should be treated with caution because it is not clear to what extent the evolutionary tracks are altered for over-contact systems. We also note that radii from the best light curve fit are significantly larger than the radii derived by the spectroscopic analysis due to the over-contact nature of the system. The errors on both the dynamical and spectroscopic masses of the two stars are relatively large. While the spectroscopic masses lead to the speculation that the two CSPNe might be AGB-manqué stars (stars that fail to evolve through the AGB), the dynamical masses do not allow us to distinguish whether one (or both) stars are post-AGB or post-red giant branch (RGB) stars. Potentially, one of them could be a post-extreme horizontal branch (EHB) star. More precise RVs and a more accurate orbital period would, therefore, be desirable to put stronger constraints on the masses.

6. Conclusions

Our preliminary results suggest that the dynamical system mass of Hen 2-428 that is derived by using all available He II lines does not exceed the Chandrasekhar mass limit. Furthermore, the individual masses of the two central stars are also too small to lead to an SN Ia in case of a dynamical explosion during the merger process. Further investigations on the red-excess and atmospheric models that consider opacities of heavy metals are mandatory for a reliable analysis this intriguing system.

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