

# The orbital period of V458 Vulpeculae, a post-double common-envelope nova

P. Rodríguez-Gil,<sup>1,2,3\*</sup> M. Santander-García,<sup>1,2,3</sup> C. Knigge,<sup>4</sup> R. L. M. Corradi,<sup>2,3</sup>  
B. T. Gänsicke,<sup>5</sup> M. J. Barlow,<sup>6</sup> J. J. Drake,<sup>7</sup> J. Drew,<sup>8</sup> B. Miszalski,<sup>8</sup> R. Napiwotzki,<sup>8</sup>  
D. Steeghs,<sup>5</sup> R. Wesson,<sup>6</sup> A. A. Zijlstra,<sup>9</sup> D. Jones,<sup>10</sup> T. Liimets,<sup>1,9</sup> T. Muñoz-Darias,<sup>11</sup>  
S. Pyrzas<sup>1,5</sup> and M. M. Rubio-Díez<sup>1,12</sup>

<sup>1</sup>Isaac Newton Group of Telescopes, Apartado de Correos 321, Santa Cruz de La Palma E-38700, Spain

<sup>2</sup>Instituto de Astrofísica de Canarias, Vía Láctea, s/n, La Laguna E-38205, Santa Cruz de Tenerife, Spain

<sup>3</sup>Departamento de Astrofísica, Universidad de La Laguna, La Laguna E-38205, Santa Cruz de Tenerife, Spain

<sup>4</sup>School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ

<sup>5</sup>Department of Physics, University of Warwick, Coventry CV4 7AL

<sup>6</sup>Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT

<sup>7</sup>Harvard–Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

<sup>8</sup>Centre for Astrophysics Research, STRI, University of Hertfordshire, College Lane Campus, Hatfield AL10 9AB

<sup>9</sup>Tartu Observatoorium, Tõravere 61602, Estonia

<sup>10</sup>Jodrell Bank Center for Astrophysics, Alan Turing Building, The University of Manchester, Oxford Road, Manchester M13 9PL

<sup>11</sup>INAF-Osservatorio Astronomico di Brera, Via E. Bianchi 46, I-23807 Merate (LC), Italy

<sup>12</sup>Centro de Astrobiología (CSIC/INTA), Ctra. de Torrejón a Ajalvir, km 4, E-28850 Torrejón de Ardoz, Madrid, Spain

Accepted 2010 June 4. Received 2010 June 2; in original form 2010 April 21

## ABSTRACT

We present time-resolved optical spectroscopy of V458 Vulpeculae (Nova Vul 2007 No. 1) spread over a period of 15 months starting 301 d after its discovery. Our data reveal radial-velocity variations in the He II  $\lambda 5412$  and He II  $\lambda 4686$  emission lines. A period analysis of the radial-velocity curves resulted in a period of  $98.09647 \pm 0.00025$  min ( $0.06812255 \pm 0.00000017$  d) which we identify with the orbital period of the binary system. V458 Vul is therefore the planetary nebula central binary star with the shortest period known. We explore the possibility of the system being composed of a relatively massive white dwarf ( $M_1 \gtrsim 1.0 M_\odot$ ) accreting matter from a post-asymptotic giant branch star which produced the planetary nebula observed. In this scenario, the central binary system therefore underwent two common-envelope episodes. A combination of previous photoionization modelling of the nebular spectra, post-asymptotic giant branch evolutionary tracks and the orbital period favour a mass of  $M_2 \sim 0.6 M_\odot$  for the donor star. Therefore, the total mass of the system may exceed the Chandrasekhar mass, which makes V458 Vul a Type Ia supernova progenitor candidate.

**Key words:** accretion, accretion discs – binaries: close – stars: individual: V458 Vul – novae, cataclysmic variables.

## 1 INTRODUCTION

V458 Vul (Nova Vul 2007 No. 1) was discovered at 9.5 mag on 2007 August 8 (Nakano et al. 2007), shortly before peaking at  $V = 8.1$ . It is classified as a fast nova on the basis of its rapid 3-mag brightness fall from maximum within 21 d, indicative of a relatively massive ( $\sim 1 M_\odot$ ) white dwarf. In our first paper (Wesson et al. 2008, hereafter W08) we reported the discovery of a wasp-waisted

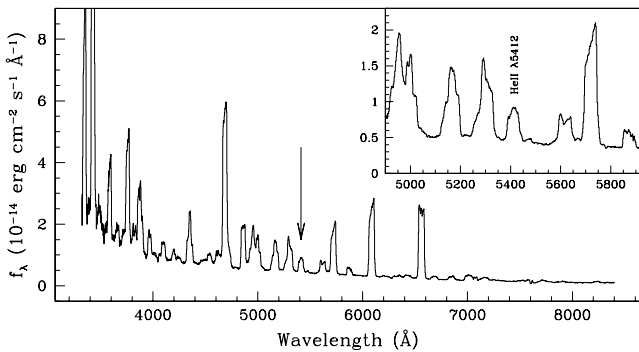
planetary nebula surrounding the  $r' = 18.34$  nova progenitor, and speculated about the possibility of the central binary star in V458 Vul being composed of a white dwarf and a post-asymptotic giant branch (post-AGB) star which formed the planetary nebula. However, the lack of an accurate orbital period prevented any further discussion. In addition, Goranskij et al. (2008) had suggested a tentative orbital period of 0.59 d from photometric light curves. In an attempt to measure a precise orbital period we started a time-resolved spectroscopy campaign searching for the orbital signature in the radial velocities of the emission lines. The results of this campaign are presented in this Letter.

\*E-mail: prguez@ing.iac.es

**Table 1.** Log of the observations.

Date	Telescope/ instrument	Grating	Slit width (arcsec)	Wavelength range	Exposure time (s)	Time coverage (h)	Dispersion ( $\text{\AA pix}^{-1}$ )	Resolution ( $\text{\AA}$ )
2008 June 04	INT/IDS	R300V	1.2	$\lambda\lambda 3320\text{--}8400$	300	5.7	1.9	5.0
2008 June 25	INT/IDS	R632V	1.5	$\lambda\lambda 4405\text{--}7150$	300	3.3	0.9	2.8
2008 July 04	WHT/ISIS	R1200B	1.0	$\lambda\lambda 4929\text{--}5644$	300	7.4	0.2	0.7
2008 October 13	INT/IDS	R300V	1.0	$\lambda\lambda 3288\text{--}8870$	300	3.6	1.9	4.4
2008 October 14	INT/IDS	R300V	1.0	$\lambda\lambda 3294\text{--}8400$	300	3.6	1.9	4.4
2008 November 11	WHT/ISIS	R600B	1.0	$\lambda\lambda 3584\text{--}5117$	300	3.7	0.9	1.5
2009 May 25	INT/IDS	R632V	1.2	$\lambda\lambda 4500\text{--}6830$	600	3.2	0.9	2.4
2009 July 21	WHT/ISIS (QUCAM3)	R600B	1.0	$\lambda\lambda 4500\text{--}4930$	30	4.4	0.4	1.5
2009 August 31	INT/IDS	R632V	1.2	$\lambda\lambda 4500\text{--}6830$	600, 800	4.0	0.9	2.4

*Notes on instrumentation:* INT/IDS: 2.5-m Isaac Newton Telescope at Roque de los Muchachos Observatory (ORM), using the IDS with a  $2000 \times 4000$  pixel E2V CCD; WHT/ISIS: 4.2-m WHT at ORM, using the IDS and Imaging System with its  $2000 \times 4000$  pixel E2V CCD.



**Figure 1.** Average of 15 spectra taken with INT/IDS on 2008 June 4 (301 d after the nova explosion). The arrow points to the He II  $\lambda 5412$  emission line, which showed significant radial-velocity shifts while the line emission was still dominated by the nova shell.

## 2 OBSERVATIONS AND DATA REDUCTION

The spectroscopic data were obtained with the Intermediate Dispersion Spectrograph (IDS) on the 2.5-m Isaac Newton Telescope (INT) and the IDS and Imaging System (ISIS) on the 4.2-m William Herschel Telescope (WHT), both on La Palma. The log of spectroscopic observations can be found in Table 1.

The spectra were reduced using the standard IRAF long-slit packages. The one-dimensional spectra were then extracted using the optimal extraction algorithm of Horne (1986). Wavelength calibration was performed in MOLLY<sup>1</sup> by means of arc lamp spectra frequently taken to guarantee an accurate wavelength solution. The spectra were then flux calibrated and dereddened using  $E(B - V) = 0.63$  (W08) using MOLLY. For the fast-spectroscopy QUCAM3 data we averaged in blocks of 10 spectra in order to achieve a proper signal-to-noise ratio for radial-velocity measurement.

## 3 EARLY RADIAL-VELOCITY VARIABILITY

The average optical spectrum of V458 Vul taken on 2008 June 4 (day 301 after the nova explosion) is shown in Fig. 1. It is mainly dominated by emission lines of [Ne v], [Fe VII], He II and the hydrogen Balmer series. The round-topped profile of the He II  $\lambda 5412$  line attracted our attention during a first visual inspection of the

line shapes. After normalizing the adjacent continuum, we cross-correlated the individual He II  $\lambda 5412$  profiles with a Gaussian template with a full width at half-maximum (FWHM) of  $400 \text{ km s}^{-1}$ . We found the radial velocity to vary between  $\sim -200$  and  $200 \text{ km s}^{-1}$ . This radial-velocity variation indicated that at least one of the components of the He II  $\lambda 5412$  emission forms in a binary system at the core of the planetary nebula. This finding prompted further time-resolved spectroscopy (see Table 1) in an attempt to measure its orbital period.

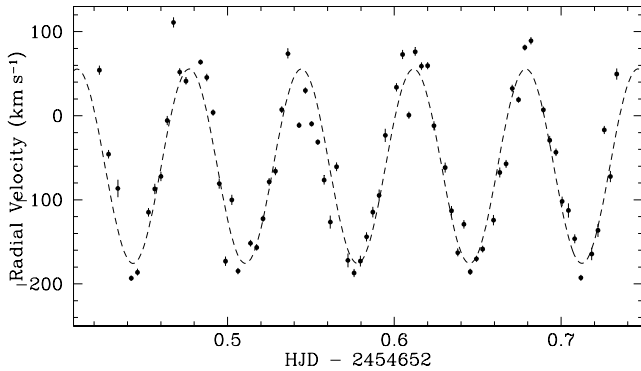
## 4 THE ORBITAL PERIOD OF V458 VUL

### 4.1 Period analysis of the radial-velocity curves

We obtained radial-velocity curves of the He II  $\lambda 5412$  emission line on 2008 June 25, July 4, October 13 and October 14. By that time no He II  $\lambda 4686$  radial-velocity variation was detected. This was not unexpected since the He II  $\lambda 4686$  line has to thin out (i.e. shed some nova ejecta emission) before it starts to present the same phenomenon as the weak, optically thin transition of the He II  $\lambda 5412$  line. The He II  $\lambda 4686$  emission showed a clear modulation by 2008 November. Therefore, we also measured radial velocities of this much brighter line on 2008 November 11 and 2009 May 25, July 21 and August 31. Before measuring the velocities, the spectra were first rebinned to constant velocity increments and continuum normalized. Radial velocities were then measured by cross-correlation with a single Gaussian template. The FWHM of the template used for a given night was adjusted so that the cleanest radial-velocity curve was obtained, but it always varied between  $400$  and  $1200 \text{ km s}^{-1}$ . The radial-velocity curve of V458 Vul exhibits a quasi-sinusoidal modulation. The longest observation (over 7 h, 2008 July 4) covers over five cycles, and a sine fit to these data results in a period of  $0.06731 \pm 0.00038 \text{ d}$  and an amplitude of  $115 \pm 5 \text{ km s}^{-1}$  (Fig. 2).

In order to refine the orbital period of V458 Vul we subjected the radial-velocity measurements to a period analysis using Schwarzenberg–Czerny’s (Schwarzenberg–Czerny 1996) variation of the analysis-of-variance method implemented as ORT in MIDAS, which fits periodic orthogonal polynomials to the phase-folded data. The periodogram calculated from the 2008 July 4 data (Fig. 3, top panel) exhibits a strong peak at  $14.86 \text{ d}^{-1}$ , consistent with the result from the sine fit mentioned above. Next, we analysed the He II  $\lambda 5412$  radial velocities, which represent about 2/3 of all our radial-velocity data and were obtained with relatively frequent sampling between 2008 June and October. The resulting periodogram (Fig. 3,

<sup>1</sup><http://www.warwick.ac.uk/go/trmarsh/software>



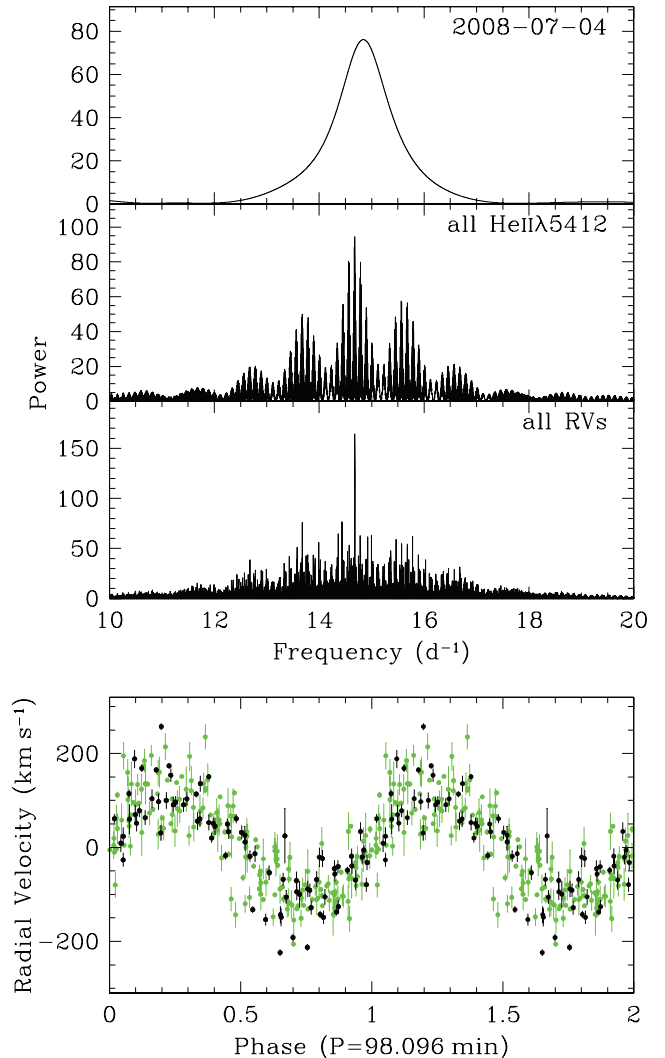
**Figure 2.** He II  $\lambda 5412$  radial-velocity curve obtained with WHT/ISIS on 2008 July 4. The velocities were measured by cross-correlating the individual profiles with a Gaussian template of  $\text{FWHM} = 400 \text{ km s}^{-1}$ . A sine fit to the data results in a period of  $0.06731 \pm 0.00038 \text{ d}$  and an amplitude of  $115 \pm 5 \text{ km s}^{-1}$ .

middle panel) contains the strongest peak at  $14.68 \text{ d}^{-1}$ , and the observed alias pattern is consistent with the window function resulting from our temporal sampling. Finally, we analysed the combined He II  $\lambda 5412$  and He II  $\lambda 4686$  data, which extend the total baseline spanned by our observations to 430 d. The resulting periodogram is characterized by a narrow spike at  $14.68 \text{ d}^{-1}$ , consistent with period determinations of the smaller radial-velocity subsets. No signal at the period claimed by Goranskij et al. was found. A sine fit to the whole data set results in  $P = 0.06812255 \pm 0.0000017 \text{ d}$  or  $98.09647 \pm 0.00025 \text{ min}$ . The He II  $\lambda 5412$  and He II  $\lambda 4686$  velocities folded on the orbital period are shown in Fig. 3 (bottom panel). Our results show that the period is coherent for 6341 cycles, suggesting that it is a fixed clock in the system. We therefore identify this period with the orbital period of the binary progenitor of nova V458 Vul, which makes it the central binary system of a planetary nebula with the shortest orbital period (see e.g. de Marco 2009, for a list).

#### 4.2 Trailed spectra diagrams

The long-term evolution of the He II  $\lambda 5412$  and He II  $\lambda 4686$  emission lines is shown in Fig. 4. He II  $\lambda 5412$  started to reveal the orbital motion of V458 Vul much earlier than He II  $\lambda 4686$ . By 2009 May, He II  $\lambda 4686$  displayed an apparent orbital signal in the form of a clear S-wave. Note that orbital phases were computed relative to the blue-to-red velocity crossing of this S-wave, which would correspond to the standard definition of the orbital phase if the S-wave originates on the donor star. The trailed spectra diagram of this line also shows high-velocity wings extending up to  $\sim \pm 1000 \text{ km s}^{-1}$ . This might indicate the presence of another emission component apart from the dominant S-wave.

A deeper look at the 2009 May spectra revealed narrow emission components bluewards of He II  $\lambda 4686$  (see Fig. 5). The first two, counting from He II  $\lambda 4686$ , lie at rest wavelengths of  $\sim 4640.6$  and  $4634.2 \text{ \AA}$  and have  $\text{FWHM} \sim 230 \text{ km s}^{-1}$ . These narrow lines, reminiscent of the radiation-driven Bowen fluorescence lines used to probe the motion of the irradiated donor star in X-ray binaries (e.g. Steeghs & Casares 2002), are in phase with the He II  $\lambda 4686$  S-wave and their radial-velocity amplitudes are comparable within what are necessarily substantial error bars. This lends further support to place these S-waves on the irradiated donor star. In V458 Vul, the white dwarf producing the nova explosion can provide the EUV radiation needed to trigger the process. In fact, two N III

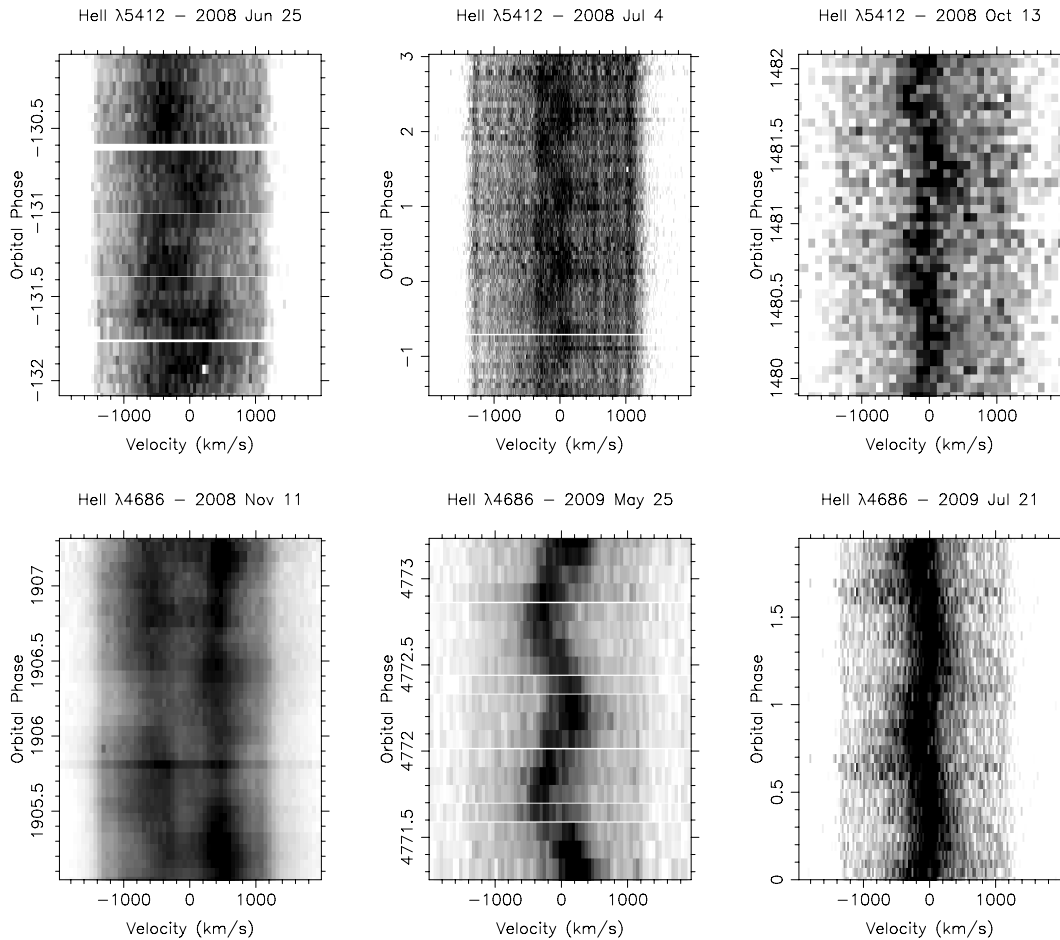


**Figure 3.** Top three panels: ORT periodograms of the single longest observation (see Fig. 2) of all the He II  $\lambda 5412$  radial velocities obtained between 2008 June and October and of all the He II  $\lambda 5412$  and He II  $\lambda 4686$  radial velocities obtained up to 2009 September. Bottom panel: mean-subtracted and phase-folded He II  $\lambda 5412$  (green) and He II  $\lambda 4686$  (black) radial velocities. The time of zero phase (blue to red crossing) is  $T_0(\text{HJD}) = 2454652.52694 \pm 8 \times 10^{-5}$ .

transitions take place at  $4640.64$  and  $4634.13 \text{ \AA}$ , very close to the observed lines. The other two emissions are likely the N v doublet lines at  $4603.74$  and  $4619.97 \text{ \AA}$ . If all these narrow lines originate on the irradiated donor star, our adopted phase convention is the correct one.

## 5 DISCUSSION AND CONCLUSIONS

In W08 we presented photoionization modelling of the nebular spectra obtained before the nova explosion ionizing the planetary nebula. This implied an ionizing source with effective temperature  $T_{\text{eff}} \simeq 90000 \text{ K}$ , luminosity  $L_{\text{bol}} \simeq 3000 L_{\odot}$  and radius  $R \simeq 0.23 R_{\odot}$ . In the same paper we showed that, based on the hydrogen-burning evolutionary tracks of Vassiliadis & Wood (1994), this requires a core mass of  $0.58 M_{\odot}$  and an age since leaving the AGB consistent with our estimated nebular expansion age of 14000 yr.



**Figure 4.** Evolution of the He II emission lines. Top panel: He II  $\lambda 5412$  trailed spectra diagrams. Bottom panel: He II  $\lambda 4686$  trailed spectra diagrams. Black represents emission. No phase binning has been applied, with the exception of the QUCAM data taken on 2009 July 21. In this last diagram a full cycle has been repeated for clarity.

The question now is which of the two stars is the progenitor of the planetary nebula? The short orbital period of V458 Vul and the age of its planetary nebula may seem at odds if one assumes the system is actually a cataclysmic variable (CV) which evolved from a much longer orbital period by losing angular momentum due to magnetic wind braking (Verbunt & Zwaan 1981; Rappaport, Joss & Verbunt 1983) and radiation of gravitational energy (Faulkner 1971; Paczyński & Sienkiewicz 1981). The time it takes a CV to evolve down to an orbital period of 98.1 min is of the order of a Gyr (Rappaport et al. 1983). However, it is possible to get a short-period, *normal* CV within a common envelope (e.g. the case of the young pre-CV SDSS J005245.11–005337.2 in Rebassa-Mansergas et al. 2008), but producing a nova event in this scenario within 14 000 yr is very unlikely.

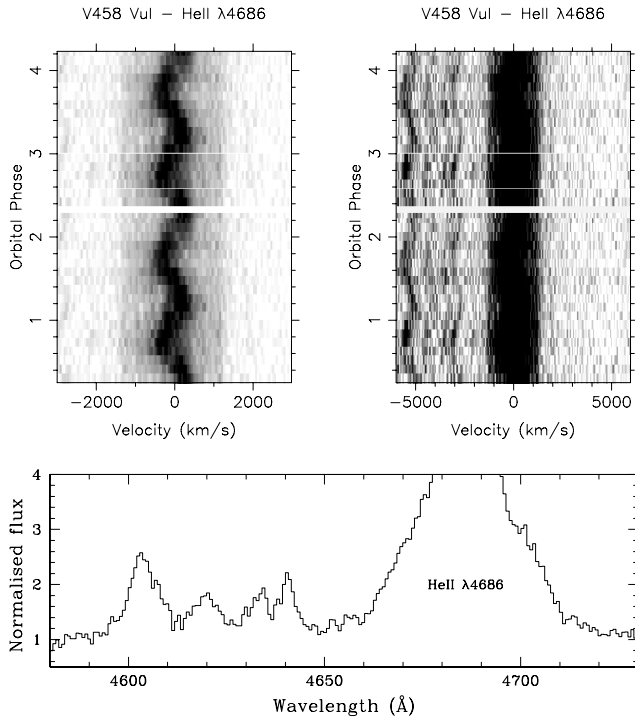
This strengthens the possibility, as suggested by W08, of the donor star in V458 Vul being actually an evolved star, i.e. a post-AGB star. In such a case, the planetary nebula of V458 Vul may have been ejected by the donor star instead of the accreting white dwarf after a second common-envelope phase. As mentioned above, the post-AGB donor would therefore have a mass of  $0.58 M_{\odot}$ .

Theoretical nova models (e.g. Prialnik & Kovetz 1995; Yaron et al. 2005) agree that a minimum white dwarf mass  $M_1 \sim 1 M_{\odot}$  is required to trigger the thermonuclear runaway in fast novae like V458 Vul. Observations, although scarce, point to a similar value (Ritter & Kolb 2003). Hence, the total mass of V458 Vul may well

be  $\gtrsim 1.6 M_{\odot}$ , above the critical Chandrasekhar mass, indicating that it may become a Type Ia supernova if the white dwarf manages to accumulate mass in the presence of nova eruptions.

Several other systems have been claimed as Type Ia supernova progenitors. The subdwarf-B+white dwarf binary KPD 1930+2752 is among the best candidates, but its total mass is very close to the critical mass (Maxted et al. 2000; Ergma, Fedorova & Yungelson 2001; Geier et al. 2007). The first He nova, V445 Puppis, may contain a binary system composed of a massive white dwarf accreting from a helium star companion (Woudt et al. 2009). The 3.9-h central binary star of planetary nebula PNG135.9+55.9 (SBS 1150+599A) has also been put forward (Tovmassian et al. 2010). In this case, a post-AGB star and, presumably, a compact companion also amount to a mass just close to the Chandrasekhar limit.

An obvious objection to our scenario is the fact that the post-AGB donor star would have to fill its Roche lobe in order to sustain mass transfer while it is still contracting. A star filling its Roche lobe must obey an orbital period–mean density law, so we used the evolutionary tracks of Blöcker (1995) in an attempt to find stellar parameters which fit both the 98-min orbit of V458 Vul and the results of our photoionization model. We find that a star with an initial and final mass of 3 and  $0.625 M_{\odot}$ , respectively, on a helium burning track at 14 000 yr, provides almost perfectly the measured effective temperature, luminosity and radius of the ionizing source. However, steady mass transfer (i.e. contact with the Roche lobe)



**Figure 5.** Top: He II  $\lambda 4686$  trailed spectra diagram of the 2009 May run after averaging into 40 phase bins. Contrast has been adjusted to highlight the main S-wave (left) and the narrow components bluewards of He II  $\lambda 4686$  (right). Black represents emission and a full cycle has been repeated for clarity. Bottom: Doppler-corrected average spectrum of the 2009 May run.

depends on the time-scales over which orbital angular momentum is lost during the second common-envelope phase and contraction of the post-AGB donor star takes place. Both processes have very short and similar time-scales (of a few thousands years), making the situation very difficult to quantify. Only further spectroscopic search for spectral lines from both components of the binary system may shed more light on to its dynamics and nature.

In conclusion, we have solidly measured an orbital period of  $98.09647 \pm 0.00025$  min for V458 Vul. A plausible scenario explaining V458 Vul is that of a double common-envelope binary

system composed of a  $M_1 \gtrsim 1 M_\odot$  white dwarf (the accretor) and a  $M_2 \sim 0.6 M_\odot$ , post-AGB star (the donor) which expelled the planetary nebula 14 000 yr ago. The total mass of the system may therefore well exceed the Chandrasekhar mass which, in addition to its close orbit, makes V458 Vul a Type Ia supernova progenitor candidate.

## ACKNOWLEDGMENTS

We thank the referee, Nye Evans, for his comments. The use of Tom Marsh's MOLLY package is gratefully acknowledged. DS acknowledges a STFC Advanced Fellowship. The WHT and the INT are operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

## REFERENCES

- Blöcker T., 1995, *A&A*, 299, 755  
 de Marco O., 2009, *PASP*, 121, 316  
 Ergma E., Fedorova A. V., Yungelson L. R., 2001, *A&A*, 376, L9  
 Faulkner J., 1971, *ApJ*, 170, L99  
 Geier S. et al., 2007, *A&A*, 464, 299  
 Goranskij V. P. et al., 2008, *Astron. Telegram*, 1631, 1  
 Horne K., 1986, *PASP*, 98, 609  
 Maxted P. F. L., Marsh T. R., Moran C. K. J., Han Z., 2000, *MNRAS*, 314, 334  
 Nakano S. et al., 2007, *IAU Circ.*, 8861, 2  
 Paczyński B., Sienkiewicz R., 1981, *ApJ*, 248, L27  
 Prialnik D., Kovetz A., 1995, *ApJ*, 445, 789  
 Rappaport S., Joss P. C., Verbunt F., 1983, *ApJ*, 275, 713  
 Rebassa-Mansergas A. et al., 2008, *MNRAS*, 390, 1635  
 Ritter H., Kolb U., 2003, *A&A*, 404, 301  
 Schwarzenberg-Czerny A., 1996, *ApJ*, 460, L107  
 Steeghs D., Casares J., 2002, *ApJ*, 568, 273  
 Tovmassian G. et al., 2010, *ApJ*, 714, 178  
 Vassiliadis E., Wood P. R., 1994, *ApJS*, 92, 125  
 Verbunt F., Zwaan C., 1981, *A&A*, 100, L7  
 Wesson R. et al., 2008, *ApJ*, 688, L21 (W08)  
 Woudt P. A. et al., 2009, *ApJ*, 706, 738  
 Yaron O., Prialnik D., Shara M. M., Kovetz A., 2005, *ApJ*, 623, 398

This paper has been typeset from a  $\text{\TeX}/\text{\LaTeX}$  file prepared by the author.