The triple degenerate star WD 1704+481

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ABSTRACT

WD 1704+481 is a visual binary in which both components are white dwarfs. We present spectra of the H$\alpha$ line of both stars which show that one component (WD 1704+481.2 = Sanduleak B = GR 577) is a close binary with two white dwarf components. Thus, WD 1704+481 is the first known triple degenerate star. From radial velocity measurements of the close binary we find an orbital period of 0.1448 d, a mass ratio, $q = M_{\text{bright}} / M_{\text{faint}}$ of $q = 0.70 \pm 0.03$ and a difference in the gravitational redshifts of $11.5 \pm 2.3$ km s$^{-1}$. The masses of the close pair of white dwarfs predicted by the mass ratio and gravitational redshift difference combined with theoretical cooling curves are $0.39 \pm 0.05 M_\odot$ and $0.56 \pm 0.07 M_\odot$. WD 1704+481 is therefore also likely to be the first example of a double degenerate in which the less massive white dwarf is composed of helium and the other white dwarf is composed of carbon and oxygen.

Key words: white dwarfs – binaries: close – stars: individual: WD 1704+481 – binaries: spectroscopic

1 INTRODUCTION

WD 1704+481 was identified as a pair of white dwarfs of similar brightness separated by about 6 arcsec by Sanduleak and Pesch (1982) from objective prism plates. Spectrophotometry of the pair by Greenstein, Dolez & Vauclair (1983) showed that, although their visual magnitudes are almost identical, the SE component (WD 1704+481.1 = Sanduleak A = GR 576, V=14.48, (B−V)=−0.09) is bluer and, therefore, hotter than the NW component (WD 1704+481.2 = Sanduleak B = GR 577, V=14.45, (B−V)=0.14). This immediately suggests that the cooler component must have a larger radius which also implies a lower mass for a cool white dwarf such as Sanduleak B. Greenstein et al. estimated a mass of $0.32 \pm 0.43 M_\odot$ for Sanduleak B which is well below the typical mass of white dwarfs ($0.55 M_\odot$, Bergheron, Saffer & Liebert 1992).

Low mass white dwarfs such as Sanduleak B are thought to be the result of binary star evolution, in which the evolution of a star during the red giant phase is interrupted by interactions with a nearby star. The physics of this interaction is complex but it is thought to lead to the stripping of the outer hydrogen layers from the red giant in a “common-envelope” phase, halting the formation of the degenerate helium core and leading to the formation of an anomalously low mass white dwarf (Iben &Livio 1993). The hypothesis that binary star evolution forms low mass white dwarfs was confirmed by the discovery of Marsh, Dhillon & Duck (1995) of at least 5 short period binary white dwarfs in a sample of 7 low mass white dwarfs.

In this paper we present spectra of the H$\alpha$ line of Sanduleak B which clearly show that it is a close binary with two white dwarf components – a double degenerate star (DD). We derive the spectroscopic orbits of both components and show that it is likely to be the first known example of a binary white dwarf with one white dwarf composed of helium and one composed of carbon and oxygen.

2 OBSERVATIONS AND REDUCTIONS.

The data for this study come from observations obtained with the 2.5m Isaac Newton Telescope (INT) in September 1998 and the 4.2m William Herschel Telescope (WHT) in October 1998. The INT spectra were obtained with the intermediate dispersion spectrograph using the 500mm camera, a 1200 line/mm grating, a 0.9 arcsec slit and a TEK charge coupled device (CCD) as a detector at a dispersion of 0.39 Å per pixel. The WHT spectra were obtained using the blue arm of the ISIS spectrograph, a 1200 line/mm grating, a 0.83 arcsec slit and an EEV CCD at a dispersion of 0.22 Å per pixel. Integration times varied between 600s and 1200s. Each observation of the stars was bracketed by observations of a copper-neon arc. We set the angle of the slit so that spectra of both stars were obtained simultaneously. The position angle estimated from this slit angle was 295°.
for the INT and 290° for the WHT, which agrees well with the PA of 289° ± 5° given by Greenstein et al. The separation of the stars measured from our INT images is 6.0 arcsec with an uncertainty of a few tenths of an arcsecond. The seeing was good for all the observations (~ 1 arcsec) so the spectra of the stars are clearly separated in all our images. Of the 49 spectra, 41 were obtained with the INT.

The bias level in all the images determined from the clipped-mean in the overscan region was subtracted from all the images before further processing. For the INT spectra, several images of a tungsten lamp were combined to form a normalized master flat-field image for each night’s data. Similar images for the WHT spectra show mild fringing. We therefore combined flat-field images taken immediately before and after each observation of the stars in order to form a normalized flat-field image for each image of the star. Extraction of the spectra from the images was performed automatically using optimal extraction to maximize the signal-to-noise of the resulting spectra (Horne 1986). Uncertainties due to photon statistics are rigorously followed through the data reduction process so that reliable uncertainties are known for every point in the final spectra. The arcs associated with each stellar spectrum were extracted using the same weighting determined for the stellar image to avoid possible systematic errors due to tilted spectra. The wavelength scale was determined from a fourth-order polynomial fit to measured arc-line positions. We calibrated the wavelength response of the WHT spectra using observations of the standard star BD +33° 2642 (Bohlin 1996). To calibrate the wavelength response of the INT spectra we used a least-squares fit of a smooth function to the ratio of the average WHT spectrum of WD 1740+481.2 and the average INT spectrum of the same star. The core of the Hα line and regions affected by telluric absorption were excluded from the fit. We then normalized all the spectra using a linear fit to the continuum either side of the Hα line.

We measured the resolution of the spectra by fitting a Gaussian profile by least-squares to a neon arc line at 6532 Å in a series of spectra. The full-width at half-maximum (FWHM) of the model profile was typically 0.94 Å for the INT spectra and 0.45 Å for the WHT spectra. The INT spectra for one night are affected by poor spectrograph focus and 0.45 ˚A (FWHM) of the model profile was typically 0.94 ˚A.

4 DISCUSSION

The first obvious result of our analysis is the mass ratio \( q = \frac{M_B}{M_C} = 0.70 \pm 0.03 \). WD 1704+481.2 is one of several double degenerates (DDs) which have been identified among low mass white dwarfs (\( M < 0.49M_\odot \)) where the fainter companion is sufficiently young, i.e., hot, for its Hα core to be detected and a mass ratio derived (Moran, Marsh & Maxted, 1999). These observed mass ratios for DDs are shown in Fig. 3. Component C has the weaker core in our spectra. The depth of the core does not vary strongly with temperature over the temperature range expected for components B and C (Koester et al. 1998), so we can confidently state that component C is the fainter component. For comparison, we also plot the results of Han (1998). We applied a set of selection criteria to the simulated population of white dwarf binaries to approximate these selection effects, namely, that the younger white dwarf is less massive than 0.49M⊙ and that the older white dwarf is younger than 1 Gyr. The mass ratio distribution for white dwarf binaries is quite similar, i.e. it shows a single peak near \( q = 0.7 \). WD 1704+481.2 lies near the peak of the theoretical distribution, which is a success for the theoretical model. What is less clear is why the majority of DDs with measured

these radial velocities showed a clear peak at 6.91 cycles per day, which confirmed our initial impression that the period is around 0.145d.

To measure the radial velocities of the two components more precisely we used a simultaneous fit to all the spectra of two model profiles, one for each star, in which the position of each model profile is predicted from a circular orbit of the form \( \gamma + K \sin(2\pi(T - T_0)/P) \). In this way we are able to determine the shape of the two profiles and the parameters of the two circular orbits directly. The (variable) resolution of each of the spectra and the effects of smearing due to orbital motion are included in the fitting process. There are many free-parameters in this fitting process so we used a series of least-squares fits in which first the profile shapes were fixed while the parameters of the orbit were varied and then vice versa, until we had established values for all the parameters which were nearly optimal. Only data within 5000 km s\(^{-1}\) of Hα and unaffected by telluric absorption are included in the fitting process. We used four Gaussian profiles to model the broad wings of the Hα line and the core of star with the deeper core and two Gaussian profiles for the other star. A polynomial is also included in the fitting process to allow for smooth, asymmetric features in the profile. For the final least-squares fit the parameters of the profile shapes and the orbit were all varied independently. The parameters of this final fit are given in Table 3. We designate the star with the deeper Hα core component B and the star with the weaker Hα core is then component C as we will refer to Sanduleak A as component A throughout to avoid confusion.

We also measured the radial velocities of Sanduleak A using the same method employed to measure the initial radial velocities of Sanduleak B. There is no significant variability in these radial velocities, which have an average value of \( \gamma A = 0.6 \pm 0.3 \) km s\(^{-1}\).
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Figure 1. Examples of our WD 1704+481.2 spectra and the least-squares fit used to derive the orbital parameters of the binary. The spectra (which are in no particular order) are offset vertically from each other for clarity and the fit is shown as a smooth line. The regions of the spectrum affected by telluric absorption and excluded from the fit are plotted with faint lines.

Figure 2. The predicted mass ratio distribution for DDs with measured mass ratios from the model of Han (1998). Measured mass ratios for double degenerates, including WD 1704+481.2 (marked with an asterisk) are indicated by error bars.

Figure 3. The predicted gravitational redshift difference, $\Delta v_{gr}$, as a function of the component masses (solid diagonal line) and its uncertainty due to the uncertainty in the mass ratio (dashed diagonal lines). The observed value of $\Delta v_{gr}$ (solid horizontal line) and its uncertainty (horizontal dashed line) are also shown.

mass ratios do not have mass ratios which accord with the models.

We can use the observed difference $\gamma_B - \gamma_C = -11.5 \pm 2.3\text{km s}^{-1}$ to determine the masses of the stars as follows.

The gravitational redshift of the light from the stars is given by $v_{gr} = 0.635(M/M_\odot)/(R/R_\odot)\text{km s}^{-1}$. Since one star is more massive than the other and more massive...
white dwarfs have smaller radii (for a given temperature), the more massive component will appear to have a larger (more positive) systemic velocity, as is observed. To determine the radius of component B we use the models of Althaus & Benvenuto (1997) for helium white dwarfs. We assume a temperature of 9500K for component B (Greenstein, Dolez & Vaucclair 1983) and use parabolic interpolation to find the radius. Note that a 1000K difference in temperature changes the radius derived by less than one percent so the temperature assumed has a negligible effect on our results. We assume that component C is slightly cooler (8500K) and use the mixed-composition models of Wood (1990) to determine its radius. In Fig. 1 we show the predicted gravitational redshift difference, \( \Delta \gamma \), as a function of the mass of each component. The observed value of \( \Delta \gamma \) is also indicated and we see that this observed value implies \( M_B = 0.39 \pm 0.05 M_\odot \) and \( M_C = 0.56 \pm 0.07 M_\odot \). White dwarfs more massive than about 0.5\( M_\odot \) will have passed through a helium-burning stage and have a carbon-oxygen composition, so these masses suggest that component B is a white dwarf composed of helium and component C is composed of carbon and oxygen. In Fig. 2 we see that the masses of the two components are roughly what would be expected from the theoretical models of Han (1998).

The mass of component C is typical for single white dwarfs (Bergeron, Saffer & Liebert 1992) and component A has the same gravitational redshift. The change in radius with temperature in this regime is very small, so we expect component A has a normal mass. Component A is \( \gtrsim 200 \) AU distant from components B and C (Greenstein et al. 1983) and the initial separation of components B and C must have been smaller than \( \sim 1 \) AU for a common-envelope phase to have occurred. The ratio of the orbital periods is sufficiently large that we need not worry about dynamical instability of the orbits (Kiseleva, Eggleton & Anosova 1994) and so we can be confident that the evolution of the inner binary will have been unaffected by the presence of component A and vice versa.

From the parameters of the orbit we find \( M_B \sin^3 i = 0.075 \pm 0.003 M_\odot \) and \( M_C \sin^3 i = 0.108 \pm 0.006 M_\odot \) which, combined with the masses derived above, yields an inclination of 61°. The separation of components B and C is only 0.74\( R_\odot \) but the small radii of white dwarfs (\( \sim 0.01 R_\odot \)) rules out the possibility of observable eclipses in this binary.

5 CONCLUSION

We have shown that WD 1704+481 is a hierarchical triple star in which all three components are white dwarfs, i.e., a triple degenerate star. The outermost star, component A appears to be a typical white dwarf. Components B and C are a close binary with an orbital period of only 0.145 d. The mass ratio \( q = \frac{M_B}{M_{\text{inert}}} = \frac{M_B}{M_C} = 0.70 \pm 0.03 \) for the inner binary is the first measured mass ratio for a double degenerate which is close to the peak of the mass ratio distribution predicted by theoretical models. Similarly, the masses of components B and C derived from the difference between their gravitational redshifts (\( M_B = 0.39 \pm 0.05 M_\odot \) and \( M_C = 0.56 \pm 0.07 M_\odot \)) appear near the peaks of the theoretical mass distributions. These suggest that the component C is a typical white dwarf composed of carbon and oxygen and that component B is composed of helium.

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