TWINS: THE TWO SHORTEST PERIOD NON-INTERACTING DOUBLE DEGENERATE WHITE DWARF STARS

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ABSTRACT

We report on the detection of the two shortest period non-interacting white dwarf binary systems. These systems, SDSS J143633.29+501026.8 and SDSS J105353.89+520031.0, were identified by searching for radial velocity variations in the individual exposures that make up the published spectra from the Sloan Digital Sky Survey. We followed up these systems with time series spectroscopy to measure the period and mass ratios of these systems. Although we only place a lower bound on the companion masses, we argue that they must also be white dwarf stars. With periods of approximately 1 hr, we estimate that the systems will merge in less than 100 Myr, but the merger product will likely not be massive enough to result in a Type Ia supernova.

Key words: white dwarfs – binaries: close – binaries: spectroscopic

1. INTRODUCTION

White dwarf stars (WDs) are the end point of stellar evolution for 98% of all stars (Weidemann 2000) and store the archaeological record of the Galaxy. WDs in binaries are particularly rich systems to study. Because of their intrinsically low luminosity the companions must also be faint, and are frequently rare or interesting objects. As an example, WDs are ideal targets for the direct detection of planets (Debes et al. 2005; Fairhi et al. 2008; Hogan et al. 2009; Mullally et al. 2009) and brown dwarf stars (e.g., Fairhi et al. 2005).

The Sloan Digital Sky Survey (SDSS; York et al. 2000) has increased the number of spectroscopically identified WDs from two thousand to a few tens of thousands. This has, in turn, allowed follow-up surveys of specific types of WD systems, from pulsators (e.g., Mullally et al. 2005; Nitta et al. 2009), to extremely low-mass WDs (Kilic et al. 2007a) to binaries involving main-sequence stars (e.g., Silvestri et al. 2006; Heller et al. 2009), and binaries with neutron stars (NSs; Agüeros et al. 2009).

Binary WDs hold the solution to an enduring problem in astrophysics; the progenitors of Type Ia Supernova (SNIa). The origin of SNIa is of great interest given their role in galactic chemical evolution and determining the nature of dark energy. If a WD accretes enough material that its mass approaches the Chandrasekhar limit (∼1.4 $M_\odot$), the star can no longer be supported by electron degeneracy pressure and explodes as a supernova. This scenario explains the lack of observed hydrogen in the spectra of SNIa, as well as the striking similarities in the light curves and spectra. However, the source of the accreted material remains a subject of active debate.

In the double degenerate scenario for SNIa progenitors (Iben & Tutukov 1984; Webbink 1984), two WDs in a tight binary in-spiral due to the emission of gravitational radiation. If the total mass is near the Chandrasekhar mass, the merger results in a supernova. While theoretically appealing, it is not clear that nature favors this method. The SPY survey (Napiwotzki et al. 2001), a high precision radial velocity survey of over a thousand WDs, failed to find any candidates with periods short enough to merge within the lifetime of the Galaxy, and masses large enough to explode as SNIa (Nelemans et al. 2005; Napiwotzki et al. 2007).

The SDSS offers an opportunity to build on the SPY survey with a much larger sample of stars. Kleinman et al. (2004) and Eisenstein et al. (2006) meticulously collected and classified the spectra of nearly 10,000 WD and sub-dwarf stars, of which approximately 8000 were single stars with hydrogen or helium atmospheres (DAs and DBs, respectively). The spectra were obtained as a series of 3 or more 15 minute exposures usually taken consecutively (Abazajian et al. 2009), which makes it possible to identify massive companions with orbital periods of a few hours or less and radial velocity amplitudes $\gtrsim 170$ km s$^{-1}$. The low luminosity of the WD means that any fainter companion must be a degenerate object (WD, brown dwarf, NS, etc.) or a very late M star; any other object would be more luminous than the white dwarf.

SWARMS (Badenes et al. 2009) exploits these individual exposures to mine the SDSS spectroscopic database for double degenerate WD (DDWD) systems. Our survey is complementary to the SPY survey in that it has a lower radial velocity sensitivity, but is still sensitive to white dwarf companions for many thousands of objects. In this Letter, we present two binary systems, SDSS J143633.29+501026.8 and SDSS J105353.89+520031.0, with periods of 1.1 and 0.96 hr, respectively. These systems constitute the shortest period non-interacting double degenerate binaries yet found, and are significantly shorter than the 1.46 hr period of the previous record holder, WD0957−666 (Moran et al. 1997). As there are no visible absorption lines from the companions our mass estimates are only lower bounds, but in each case the companion is most likely another WD.

2. OBSERVATIONS AND REDUCTIONS

We identified SDSS 1436 ($g = 18.2$, plate-mjd-fiber=1046-52460-594) and SDSS 1053 ($g = 18.9$, 1010-52649-12) as hydrogen atmosphere (DA) WDs potentially possessing short period companions as part of an on-going survey for DDWDs. Although we see radial velocity variations between different exposures, no companion is visible in the spectrum. To confirm these systems as binaries, and to measure the orbital parameters, we observed both stars with the Dual Imaging Spectrograph (DIS) with the 3.5 m telescope at Apache Point Observatory over four nights between 2009 February 5 and 2009 February 14. We used the B1200 grating with a 1.5′′ slit for a dispersion of 0.62 Å per pixel and a resolution of 1.8 Å FWHM. Each exposure...
De-shifted and co-added spectrum of SDSS 1436 based on observations made at APO. The solid red line is the best-fit model used to estimate the temperature and gravity. The average S/N per pixel in this spectrum is 30, and \( \approx 7 \) in each individual spectra.

Table 1

| Measured Parameters | SDSS 1436 | SDSS 1053 |
|---------------------|-----------|-----------|
| Period (hr)         | 1.15238(14) | 0.960(10) |
| Amplitude (km s\(^{-1}\)) | 388(21) | 310(14) |
| Separation (R\(_{\odot}\)) | 0.4789(75) | 0.2924(51) |
| \( T_{\text{eff}} \) (K) | 17120(200) | 16150(200) |
| \log g          | 6.60(05) | 6.35(05) |
| Mass\(_1\) (M\(_{\odot}\)) | 0.23(01) | 0.22(01) |
| Mass\(_2\)/\text{sin }i (M\(_{\odot}\)) | 0.57(04) | 0.31(02) |
| Merge time (Myr) | <102 | <104 |

Examination of the unfolded light curve confirms this trend is indeed a function of phase, not of time, and cannot be explained by some drift in our instrumental calibration. Similarly, a third body in the system on a longer period orbit would only produce a trend in the unfolded data. Fitting an eccentric orbit reduces the peak-to-peak amplitude of the residual trend by 100 km s\(^{-1}\) but does not eliminate it. Because the eccentric orbit fit is not significantly better, and because we have difficulty imagining a scenario in which a system that has undergone two common envelope evolution phases could emerge with an eccentric orbit, we show only the circular fit in Figure 2.

2.1. Temperature and Gravity

The published temperature of each star from Eisenstein et al. (2006) comes from a fit to the average of three separate exposures spanning a total of 50 minutes. As this is a significant fraction of the orbital period we were concerned that the fit may have been biased by combining spectra with different radial velocities. Using our best-fit radial velocity curve, we deshifted and co-added each of our 10 minute exposures to produce a high signal-to-noise spectrum. We then fit this spectrum to the same
grid of DA models used by Eisenstein et al. (2006) (updated by Koester et al. 2009, and kindly provided by the author). We linearly interpolated the model spectra to produce a finer grid of $\Delta T_{\text{eff}} = 10$ K and $\Delta \log g = 0.02$. We fit each model to the entire spectrum from 3800–5000 Å using a least squares minimization algorithm, allowing the fit to vary by a high order polynomial in a similar manner to Eisenstein et al. (2006). We find best-fit parameters of 17120 K, $\log g = 6.60$ for SDSS 1436 and 16150 K, 6.35 for SDSS 1053, consistent with the estimate of Eisenstein et al. (2006) who finds $(T_{\text{eff}}, \log g)$ of $(16933, 6.58)$ and $(15399, 6.28)$, respectively.

For each object we combine spectra taken close to the minima and maxima of the velocity curve. We find no evidence of spectral features in these combined spectra and are confident that flux from the companion is not biasing our fit. Fontaine et al. (2003) noted that temperature and gravity estimates of WDs from independent spectra using identical reductions and identical atmosphere models often disagree significantly more than the quoted uncertainties. Following their approach, we adopt uncertainties of 200 K and 0.05 for our fits, which are more conservative than the values returned by the fitting method. We caution that these uncertainties are internal to our fitting, and do not attempt to address limitations of the models. For example, Tremblay et al. (2009) recently introduced an improved treatment of Stark broadening which systematically increases the best-fit gravity by 0.2 dex in this temperature and gravity range.

Kilic et al. (2007a) independently observed and fit the spectra of both stars (as part of a search for companions to low-mass WDs) and obtained similar results for the gravity ($\log g = 6.59$ and 6.40), but higher temperatures ($T_{\text{eff}} = 18339$ and 18325). Given the close agreement in measured gravity between the three measurements, the small discrepancy in temperatures does not materially affect the stellar masses we estimate in Section 3.

We simulated the effect of changing radial velocities over the course of a 10 minute exposure to estimate the effect on the best-fit temperature and gravity. Using our best-fit radial velocity curve for SDSS 1436, we co-added a series of appropriately Doppler-shifted model spectra, and fit the result in a manner similar to our data. The largest discrepancy occurs when the star is traveling perpendicular to the line of sight, where the core of the line appears smoothed. This blurred spectrum is preferentially fit by a 500 K hotter model with a shallower line core, but the best-fit gravity, which is most important for measuring the mass, remains unchanged.

3. DISCUSSION

Comparing our best-fit temperature and gravity to the WD evolution models of Serenelli et al. (2002) we estimate masses of 0.23(01) and 0.21(01) $M_{\odot}$. These models are created by removing mass from a 1 $M_{\odot}$ model at appropriate times during red giant branch evolution, and incorporate chemical diffusion, a nearly pure He core (with metallicity, $Z = 0.001$) and a thick H layer. The estimated masses are close to the minimum known white dwarf mass of 0.17 $M_{\odot}$ (Kilic et al. 2007a; Kawka & Vennes 2009). Moroni & Straniero (2009) estimate that a WD must have a mass of at least 0.33 $M_{\odot}$ to have a carbon–oxygen core. Neither object approaches this mass, and are composed almost entirely of helium with a thin hydrogen atmosphere.

According to the initial–final mass relation (e.g., Kalirai et al. 2008; Williams et al. 2009), only isolated WDs with masses greater than 0.47 $M_{\odot}$ have had time to evolve off the main sequence within the lifetime of the universe. Although it has been argued that high metallicity progenitors can produce lower mass WDs (Kilic et al. 2007c), that scenario is unnecessary for these systems. Instead, the fact that these two systems are known to be binaries suggests that growth of these lower mass WDs was truncated by a common envelope phase and evolved through the sub-dwarf channel (Heber 2009).

3.1. Nature of the Companions

Solving for the Keplerian equations of motion for SDSS 1436 gives a mass for the companion of $(0.57(04)/\sin i) M_{\odot}$, where $i$ is the inclination of the orbit to the line of sight, consistent with a carbon–oxygen core WD. The companion to SDSS 1053 is at least 0.31(02) $M_{\odot}$. Although these are minimum masses, and are consistent with a wide range of astrophysical objects, we argue that the companions are most likely also WDs.

Main-sequence stars can be ruled out on luminosity grounds. For SDSS 1436 (SDSS 1053), the minimum mass of the companion corresponds to a spectral type of K8 (M1) (Habets & Heintze 1981), which has an absolute $i$ magnitude of 7.2 (8.5) (Bilir et al. 2009; Hawley et al. 2002), considerably brighter than the observed WD ($i = 9.1(9.4)$, Holberg & Bergeron 2006). The SDSS spectrum of either object shows no evidence of any cool companion at red wavelengths, ruling out the possibility of a main-sequence companion. A similar argument applies to red giant stars and other higher luminosity objects.

If the inclination angle, $i < 24^\circ(13^\circ)$, the companion mass is greater than the Chandrasekhar mass and the companion must be an NS or a black hole. Approximately 45 WD-NS binaries are known, and the mass distribution of WDs in such binaries is much wider than for isolated systems, admitting both high- and low-mass WDs (van Kerkwijk et al. 2005). Agüeros et al. (2009) looked at both SDSS 1436 and SDSS 1053 during an 820 MHz radio survey for pulsar companions to WDs but did not detect any signal. These observations do not exclude the possibility of a pulsar companion, not only because the orientation of the pulsar beam may not be along the line of sight, but also because their analysis restricted their sensitivity to orbital periods greater than 8 hr.

Interacting WD-NS binaries are known as ultra-compact X-ray binaries (UCXBs; see Nelmans & Jonker 2006, for a review). In these systems, the orbital separation is so small that a WD overfills its Roche lobe and donates material onto the surface of the NS via an accretion disk, emitting X-rays in the process. The longest period UCXBs have periods of 50–55 minutes (Nelmans & Jonker 2006), entirely consistent with the periods of the systems under scrutiny. If the companions were NSs, they would almost certainly be interacting. However, the presence of hydrogen in the atmosphere of the visible WD in both systems means that the systems are not interacting. In double degenerate systems, mass transfers from the lower to the higher mass star. In both systems, the higher mass star is the invisible companion. If the visible star was losing mass, the thin hydrogen layer would be quickly stripped, exposing the underlying helium core. Because both stars still have their hydrogen layers we can conclude that mass transfer has not yet started.

3.2. Consequences of a Merger

Non-interacting WD companions are therefore the only possible objects consistent with the available evidence. Non-interacting systems in short period orbits lose orbital energy in the form of gravitational radiation and will eventually merge (see
and no supernova. Is burned into oxygen, but there is no thermonuclear runaway carbon–oxygen core star (similar to SDSS 1436), some carbon–oxygen WD with a He core one has been suggested were created by the merger of lower mass stars. The merger of sub-dwarf stars (Heber2009). Regardless, the merger remnant 2007). The merger of two helium core WDs (an option only 339, 2.535, and probably produce a high-mass WD.

4. CONCLUSION

We report on the detection of the two closest non-contact white dwarf binaries known. These systems were detected by mining the spectroscopic database of the SDSS, and followed-up with time-resolved optical spectroscopy. We argue that the companions must also be WDs: Main-sequence stars of the requisite mass are more luminous than the primary WDs, and an NS or a black hole in such close proximity would have stripped off the thin outer layers of the primaries. With periods of about an hour, these systems will merge in less than 100 Myr and probably produce a high-mass WD.

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Figure 4. Distribution of known DDWD systems. The filled circles indicate the minimum mass of the two new systems discussed in this Letter. The notch on the arrow gives the total mass assuming an inclination angle, , of 60°, and the tip of the arrow shows . Square symbols indicate previously known double-lined (DL) binaries (where the total mass is known), while triangles indicate single-lined (SL) systems and are only a lower bound on the total system mass. SDSS J091709.55+463821.8 (open triangle) taken from Kilic et al. (2007b), and all other systems from Nelemans et al. (2005). The horizontal dashed line indicates the Chandrasekhar mass, while the curved line shows the period for which the merger time is equal to the age of the universe.
