A new gravitational wave verification source

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ABSTRACT

We report the discovery of a detached 20-min orbital period binary white dwarf (WD). WD 0931+444 (SDSS J093506.93+441106.9) was previously classified as a WD + M dwarf system based on its optical spectrum. Our time-resolved optical spectroscopy observations obtained at the 8 m Gemini and 6.5 m MMT reveal peak-to-peak radial velocity variations of ≈400 km s⁻¹ every 20 min for the WD, but no velocity variations for the M dwarf. In addition, high-speed photometry from the McDonald 2.1 m telescope shows no evidence of variability nor evidence of a reflection effect. An M dwarf companion is physically too large to fit into a 20 min orbit. Thus, the orbital motion of the WD is almost certainly due to an invisible WD companion. The M dwarf must be either an unrelated background object or the tertiary component of a hierarchical triple system. WD 0931+444 contains a pair of WDs, a 0.32 M⊙ primary and a ≥0.14 M⊙ secondary, at a separation of ≥0.19 R⊙. After J0651+2844, WD 0931+444 becomes the second shortest period detached binary WD currently known. The two WDs will lose angular momentum through gravitational wave radiation and merge in ≤9 Myr. The log h ≈ −22 gravitational wave strain from WD 0931+444 is strong enough to make it a verification source for gravitational wave missions in the milli-Hertz frequency range, e.g. the evolved Laser Interferometer Space Antenna (eLISA), bringing the total number of known eLISA verification sources to nine.

Key words: gravitational waves – binaries: close – stars: individual (SDSS J093506.93+441106.9, WD 0931+444) – white dwarfs.

1 INTRODUCTION

Short period binary white dwarfs (WDs) are expected to dominate the gravitational wave foreground at mHz frequencies. Nelemans (2013) predicts ~10⁶ double WDs in the Galaxy, including several thousand sources that should be individually detected by evolved Laser Interferometer Space Antenna (eLISA; Amaro-Seoane et al. 2012). However, there are only eight eLISA verification sources currently known. All but one of these are AM Canum Venaticorum binaries (e.g. Solheim 2010) with orbital periods ranging from 5 to 27 min. The remaining system is the 12-min orbital period detached binary J0651+2844 (Brown et al. 2011; Hermes et al. 2012).

Low-mass (M < 0.45 M⊙) WDs are signposts of short period binary systems (e.g. Marsh, Dhillon & Duck 1995; Napiwotzki et al. 2007). We established a radial velocity programme, the Extremely Low Mass (ELM) Survey (Brown et al. 2010, 2012, 2013; Kilic et al. 2010, 2011, 2012), to identify short period binary WDs that are strong gravitational wave sources and potential progenitors of Type Ia and .Ia supernovae (Bildsten et al. 2007; Shen & Bildsten 2009; Kilic et al. 2014). The ELM Survey has so far discovered 55 binaries, all with P ≤ 1 d, including 32 that will merge within a Hubble time (Gianninas et al. 2014). Three of these have orbital periods less than an hour; J0651+2844, J0106−1000, and J1630+4233.

We have recently extended our search for ELM WDs to the Sloan Digital Sky Survey Data Release 10 (SDSS DR10; Ahn et al. 2014).
We fit all available DR10 spectroscopy for stellar sources with WD model spectra (Koester 2010) to identify ELM WDs with $5 \leq \log g \leq 7$ and $M \leq 0.3 M_\odot$. Here, we present optical spectroscopy and photometry of one of these sources, the relatively bright ($g = 17.7$ mag) SDSS J093506.93+441106.9 (WD 0931+444).

Usher, Mattson & Warnock (1982) identified WD 0931+444 as a UV-excess object in the Palomar Schmidt plates, and Mitchell & Usher (2004) confirmed it as a DA WD based on optical spectroscopy. However, the SDSS observations clearly show a composite spectrum of a DA WD plus an M dwarf (Kleinman et al. 2013). Silvestri et al. (2006), Rebassa-Mansergas et al. (2007, 2010), and Heller et al. (2009) classify WD 0931+444 as a low-mass WD with $T_{\text{eff}} \sim 20,000$ K, $\log g \approx 7$, and an M1 dwarf companion. Rebassa-Mansergas et al. (2007) find an average mass and radius of $M = 0.46 M_\odot$ and $R = 0.43 \pm 0.09 R_\odot$ for M1 dwarfs, which implies a distance of $1440 \pm 340$ pc for the M dwarf in WD 0931+444. Rebassa-Mansergas et al. (2010) revise the distance to $\approx 1150 \pm 220$ pc, which is $2.2 \sigma$ farther away than the WD (see Section 3.1). However, there seems to be a systematic effect that leads to overestimating the M dwarf distances in DA + M systems (see Rebassa-Mansergas et al. 2010). For example, the distance estimates for the WDs and M dwarfs in the 58 post-common-envelope binaries presented in Nebot-Gómez-Morán et al. (2011) differ by as much as $3 \sigma$. Hence, the inconsistent distance estimates for the WD and M dwarf do not rule out physical association. Rebassa-Mansergas et al. (2007) also point out that the M dwarf in WD 0931+444 has a poorly defined Na I doublet, possibly due to orbital motion. If so, the relatively hot WD would cause significant heating of the secondary star, which would be detected as a reflection effect in the optical light curve.

Our radial velocity and high-speed photometry demonstrate that WD 0931+444 contains a pair of WDs with an orbital period of only 20 min, and that the M dwarf is not a member of this binary. In Section 2, we describe our spectroscopic and photometric observations. In Sections 3 and 4, we constrain the physical parameters of this system and discuss the nature and future evolution of WD 0931+444. We conclude in Section 5.

2 OBSERVATIONS

We used the 6.5-m MMT with the Blue Channel spectrograph to obtain medium resolution spectroscopy of WD 0931+444 in 2013 November and 2014 March. The former observations used the 832 line mm$^{-1}$ grating in second order, providing wavelength coverage from 3600 to 4500 Å and a spectral resolution of 1.2 Å. The latter observations used the 1200 line mm$^{-1}$, providing wavelength coverage from 5640 to 6940 Å and a spectral resolution of 1.5 Å. We obtained all observations at the parallactic angle.

We obtained follow-up optical spectroscopy using the 8-m Gemini-North telescope with the Gemini Multi-Object Spectrograph in 2014 March as part of programme GN-2013B-DD-9. We obtained a sequence of 32×150 s exposures with the R831 grating and a 0.5 arcsec slit, providing wavelength coverage from 5460 to 7560 Å and a resolving power of 3720. We also obtained a sequence of 20×120 s exposures with the B1200 grating and a 0.5 arcsec slit, providing wavelength coverage from 3700 to 5150 Å and a resolving power of 3635. Each spectrum has a comparison lamp exposure taken within 10 min of the observation time. We flux-calibrate using blue spectrophotometric standards (Massey et al. 1988), and measure radial velocities using the cross-correlation package RVSAO.

We acquired high-speed photometry of WD 0931+444 using the McDonald 2.1-m Telescope with the Puoko-nui North camera.

3 RESULTS

3.1 The ELM WD

Fig. 1 shows the optical spectrum of WD 0931+444 along with our model fits. The optical spectrum is dominated by the WD below 5000 Å, which enables us to use the Balmer lines to constrain the physical parameters of the WD precisely. We use the H$\gamma$–H12 lines in our MMT spectra and an extended model atmosphere grid based on the Bergeron, Wesemael & Beauchamp (1995) models, with recent improvements presented in Tremblay & Bergeron (2009), to constrain the atmospheric parameters of the WD. The best-fitting model has $T_{\text{eff}} = 21,660 \pm 380$ K and $\log g = 6.96 \pm 0.05$. The recent evolutionary calculations by Althaus, Miller Bertolami & Córso (2013) indicate that WD 0931+444 is an M $= 0.32 \pm 0.02 M_\odot$ and $R = 0.031 \pm 0.003 R_\odot$ WD at a distance of 660 ± 70 pc.

The right-hand panel in Fig. 1 shows composite WD + M dwarf model fits to the SDSS spectrum of WD 0931+444. We use the best-fitting WD model to subtract out the contribution from the WD and use the Bochanski et al. (2007) templates to fit the contribution from the M dwarf. The best-fitting template is M1.5, consistent with the previous analyses by Silvestri et al. (2006), Heller et al. (2009), and Rebassa-Mansergas et al. (2010). This spectral type is also consistent with the infrared data from the Two Micron All Sky Survey (Cutri et al. 2003) and the Wide-Field Infrared Survey Explorer (Wright et al. 2010).

3.2 The orbital period

Fig. 2 shows Gemini time-resolved spectroscopy of H$\gamma$ and H$\beta$ lines over 45 min. H$\beta$ and higher order Balmer lines are relatively clean, with no evidence of significant contamination or activity from the M dwarf. All of the Balmer lines clearly show evidence of a 20-min orbital period.

Fig. 3 shows 55 radial velocity measurements for WD 0931+444 obtained from H$\gamma$ through H12 lines. Table 1 lists these velocities. We compute the best-fitting orbital elements using the code of Kenyon & Garcia (1986), and perform a Monte Carlo analysis to verify the uncertainties in the orbital parameters (see Brown et al. 2012 for details). WD 0931+444 exhibits radial velocity variations with a semi-amplitude of $K = 185.4 \pm 3.2$ km s$^{-1}$ and
Gemini time-resolved spectroscopy of the Na\textsc{i} orbital cycles in this figure, consistent with $-\alpha$ in all of the $z\alpha^2 + 2001 - \alpha$ companion is 97.5 per cent. Hence, the companion line (right-hand panel) over 90 min. The Na$\textsc{i}$ doublet is consistent with $\leq i$ line from the M dwarf are stationary, whereas the H$\alpha$ line from the Na$\textsc{i}$ I $90 70 4k ms \approx$ shows the McDonald 2.1-m telescope light curve of + doublet (left-hand panel) and the H$\alpha$ line (right-hand panel) over 90 min. The Na$\textsc{i}$ lines and $z\alpha$ lines clearly show a 20-min periodicity. The radial velocities of the Balmer lines in WD 0931+444 are stationary. While the second one, from the WD, is almost certainly another WD.

3.3 The M dwarf in WD 0931+444

At an inclination angle of $i = 90^\circ$, a 0.13 M$_{\odot}$ companion would have a Roche lobe radius of 0.056 R$_{\odot}$ (Eggleton 1983). This is smaller than the radii for all known M dwarfs (see table 5 in Rebassa-Mansergas et al. 2007). Hence, if the orbital motion of WD 0931+444 is due to an M dwarf, such a companion would fill its Roche lobe, yet there is no evidence of mass transfer in this system. In fact, no main-sequence star can fit into this orbit; the orbital period of this system is significantly shorter than the period minimum for cataclysmic variables ($\approx 78$ min; Hellier 2001). Clearly, the visible M dwarf in WD 0931+444 cannot be a binary companion of the WD. Based on the mass function alone, the probability of a M $\leq 1.4 M_{\odot}$ companion is 97.5 per cent. Hence, the companion is almost certainly another WD.

3.4 The light curve

Fig. 5 shows the McDonald 2.1-m telescope light curve of WD 0931+444. The Fourier transforms of the blue-sensitive $BG40$ and the red-sensitive SDSS $z$-band data are also shown. These light curves do not reveal any significant photometric variability. There is a marginal peak ($<3\sigma$) at 1203.6 s in the $BG40$ filter data. This is consistent with variations at the orbital period, which may be due to the relativistic beaming effect. Similarly, there is a marginal peak in the $z$-band data at 1758.2 s. No variations are expected at that frequency, hence this marginal signal is most likely due to noise from atmospheric variability in the $z$-band.

Assuming that the secondary star has a radius comparable to the ELM WD, the lack of eclipses in our photometry require $i \leq 70^\circ$,

Table 1. Radial velocity measurements for WD 0931+444. The full table is available online as supplementary information.

| HJD−2456500 | $v_{\text{helio}}$ (d) (km s$^{-1}$) |
|-------------|----------------------------------|
| 97.029593   | 104.34 ± 23.31                   |
| 98.029345   | 191.50 ± 30.83                   |
| 99.023102   | 199.16 ± 25.51                   |
| 99.023970   | 84.95 ± 35.74                    |
| 99.024850   | −16.74 ± 39.36                   |
which implies a $M \geq 0.14 M_\odot$ WD companion. For $i \leq 70^\circ$ and the limb- and gravity-darkening coefficients of $\alpha = 0.34$ (Gianninas et al. 2013) and $r = 0.48$, respectively, we expect $\leq 0.25$ percent ellipsoidal variations in the $BG40$ filter due to tidal distortions of the primary. This amplitude is below our detection threshold, so the lack of a signal at half the orbital period does not provide any new constraints on the inclination of the binary.

The absence of a reflection effect is additional evidence that the M dwarf does not orbit the WD. For comparison, HS 2043$+$0615 is a $T_{\text{eff}} \approx 26000$ K subdwarf star with a $0.18$--$0.34 M_\odot$ M dwarf companion in a 0.3 d binary. This system shows 0.15 mag brightness variations due to the reflection effect (Geier et al. 2014). Similarly, SDSS J162256.66$+$473051.1 contains a subdwarf star with a heated brown dwarf companion in a 0.07 d orbit, and shows a $\sim 10$ per cent reflection effect (Schaffenroth et al. 2014). Yet, there is no evidence of a reflection effect for WD 0931$+$444 in our photometry. This further reinforces our determination that the M dwarf is not in the 20-min orbit with the visible WD.

4 DISCUSSION

4.1 A new verification binary

Our optical spectroscopy and photometry demonstrate that WD 0931$+$444 is a 20-min orbital period detached double WD. Along with J0106$-$1000, J0651$+$2844, and J1630$+$2433, WD 0931$+$444 becomes the fourth detached WD binary known to have a period less than an hour. The two WDs in this system will merge in $\approx 9$ Myr. After J0651, WD 0931$+$444 becomes the second quickest WD merger system currently known.

At a distance of 660 pc and $i \leq 70^\circ$, we expect the gravitational wave strain at Earth $\log h \geq -22.17$ at log $v (\text{Hz}) = -2.77$ (Roelofs et al. 2007). Hence, WD 0931$+$444 is clearly a verification source for eLISA, bringing the total number of known eLISA verification sources to nine.

When the mass transfer starts, WD 0931$+$444 will most likely have unstable mass transfer (Marsh, Nelemans & Steeghs 2004). However, the merger outcome is uncertain because of the unknown inclination angle and the companion mass. For a relatively high inclination angle of $i \approx 70^\circ$, the companion would be a very low mass WD with $M = 0.14 M_\odot$, and the merger will lead to a single He-burning subdwarf star. For an inclination of $i = 31^\circ$, WD 0931$+$444 would be an equal mass binary with a merger time of 4.4 Myr, and $\log h = -21.6$. This is similar to the gravitational wave strain from the verification binary HP Lib (Nelemans 2006). The non-detection of the secondary WD in our spectroscopy implies that the companion is cooler (like CS 41177; Bours et al. 2014) and/or more massive (like J0651; Brown et al. 2011). Therefore, the gravitational wave strain of WD 0931$+$444 may be even higher than this estimate, potentially making it one of the best verification sources known.

4.2 Is WD 0931$+$444 a triple system?

There is growing interest in triples containing an inner double WD binary. Perets & Kratter (2012) suggest that mass-loss in an evolving triple system leads to orbital instability, triggering close encounters or collisions in the system. This mechanism could explain prompt supernovae Ia, and contribute to the Ia event rate (Kushnir et al. 2013). However, Hamers et al. (2013) find this rate to be low.

To explore the eccentricity of the WD 0931$+$444 binary, we fit both circular and eccentric orbits to the radial velocity data. The $3\sigma$ upper limit on eccentricity is $e = 0.02$, and the Lucy & Sweeney (1971) test strongly prefers a circular orbit. This suggests that the Kozai mechanism is not important for WD 0931$+$444, and we are yet to find a triple system containing an eccentric double WD inner binary.

Given the size of the orbit ($0.19 R_\odot$), and the lack of evidence for mass transfer and a reflection effect, the M dwarf that contaminates the SDSS spectrum of WD 0931$+$444 cannot be a member of the 20-min period binary. The distance estimate also puts the M dwarf significantly further away than the WD, though the distance uncertainty is rather large. Cross-correlating with a template spectrum of an inactive M1 dwarf (Bochanski et al. 2007), we measure velocities of $-47 \pm 9$ and $-37 \pm 13$ km s$^{-1}$ for the Nai doublet from the Gemini and MMT spectra, respectively. These are significantly different than the systemic velocity of the WD binary ($74.3 \pm 2.3$ km s$^{-1}$). Hence, the M dwarf is likely a background source.

Based on six epochs from the USNO-B and the SDSS, Munn et al. (2004) measure a proper motion of $(\mu_\alpha \cos \delta, \mu_\delta) = (-19.9, -0.8)$ mas yr$^{-1}$. WD 0931$+$444 is unresolved in the Palomar plates and the SDSS images. If the proper motion measurement is correct, WD 0931$+$444 would have moved only 1 arcsec between the first Palomar observations and the SDSS. Hence, the current proper motion measurements are inconclusive in deciding if the M dwarf is the tertiary component of the WD 0931$+$444 system. If the M dwarf is a background object, the Hubble Space Telescope observations may be able to resolve the WD and the M dwarf and confirm or rule out any physical association based on common proper motion.

5 CONCLUSIONS

We identify WD 0931$+$444 as a new eLISA verification source, only the ninth such system known. WD 0931$+$444 is a 20-min orbital period detached binary WD, the second quickest merger system currently known. It contains a $0.32 M_\odot$ WD and a $\geq 0.14 M_\odot$ companion. The M dwarf in this system may or may not be associated with WD 0931$+$444, and we propose follow-up proper motion
measurements to distinguish between the two scenarios. Since the companion WD is not detected in our spectroscopy or photometry, it is likely cooler and/or more massive than the ELM WD. A more massive companion would make it one of the strongest sources of gravitational radiation currently known.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 1. Radial velocity measurements for WD 0931+444

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