

THE RUNAWAY WHITE DWARF LP400–22 HAS A COMPANION

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ABSTRACT

We report the detection of a radial velocity companion to the extremely low-mass white dwarf (WD) LP400–22. The radial velocity of the WD shows variations with a semiamplitude of 119 km s^{-1} and a 0.98776 day period, which implies a companion mass of $M \geq 0.37 M_{\odot}$. The optical photometry rules out a main-sequence companion. Thus the invisible companion is another WD or a neutron star. Using proper-motion measurements and the radial velocity of the binary system, we find that it has an unusual Galactic orbit. LP400–22 is moving away from the Galactic center with a velocity of $396 \pm 43 \text{ km s}^{-1}$, which is very difficult to explain by supernova runaway ejection mechanisms. Dynamical interactions with a massive black hole like that in the Galactic center can in principle explain its peculiar velocity, if the progenitor was a triple star system comprised of a close binary and a distant tertiary companion. Until better proper motions become available, we consider LP400–22 to be most likely a halo star with a very unusual orbit.

Key words: binaries: close – stars: individual (LP400–22) – white dwarfs

1. INTRODUCTION

In recent years, the number of known white dwarfs (WDs) has grown significantly. Optical spectroscopy shows that most of these objects are hydrogen-atmosphere WDs with a mass distribution that peaks at $0.6 M_{\odot}$ (Eisenstein et al. 2006; Kepler et al. 2007). Among the new WDs, there are also a handful of extremely low-mass (ELM) WDs with $M \leq 0.3 M_{\odot}$ (Liebert et al. 2004; Eisenstein et al. 2006; Kilic et al. 2007a). ELM WDs are rare, comprising $\leq 0.2\%$ of spectroscopically confirmed WDs. More importantly, single star evolution cannot produce such low-mass WDs in the age of the Galaxy. Thus, these WDs yield interesting tests of stellar evolution theory.

ELM WDs must undergo significant mass loss during their formation. In one scenario, they form in close binaries whose evolution includes a phase of mass transfer, during which much of the WD progenitor’s envelope is removed. This prevents a helium flash in the progenitor’s core and results in the observed low-mass, helium-core WD (e.g., Marsh et al. 1995). Existing observations of ELM WDs do not detect the photometric excess or the spectroscopic signature expected from main-sequence companions. Hence, the binary companions of known ELM WDs are probably either WDs or neutron stars. This result is consistent with spectroscopic studies of large samples of hydrogen-atmosphere WDs, which conclude that in the majority of cases low-mass WDs are likely to have degenerate companions (e.g., Liebert et al. 2005; Nelemans & Tout 2005). ELM WDs are also frequent companions to millisecond pulsars (MSPs), although in these radio-selected systems the WDs are frequently too faint for optical spectroscopy to confirm that they are indeed WDs (e.g., discussion in van Kerkwijk et al. 2005).

In another scenario, low-mass WDs form from the evolution of single, metal-rich stars. Kilic et al. (2007c) estimate that the binary fraction for WDs with $M \sim 0.4 M_{\odot}$ is 50%. They also predict that the binary fraction rises to 100% for WDs

with $M < 0.2 M_{\odot}$, since such extreme mass-loss rates are not expected even for the most metal-rich stars in the Galaxy. Spectroscopic radial velocity studies of the newly discovered low-mass WDs are therefore essential if we are to discriminate between these mass-loss scenarios by measuring the binary fraction of low-mass WDs and/or to characterize the currently unseen companions.

A radial velocity study of Sloan Digital Sky Survey (SDSS) J091709.55+463821.8 (hereafter SDSS J0917+46), the lowest gravity WD currently known, revealed velocity variations with an orbital period of 7.6 hr. The companion of SDSS J0917+46 is most likely another WD, although a neutron star companion is not completely ruled out (Kilic et al. 2007b).

In this Letter, we describe a radial velocity study of another ELM WD, LP400–22 (also known as WD 2234+222 and NLTT 54331). This star is interesting because of its low mass ($\approx 0.17 M_{\odot}$) and also because of its high tangential velocity (greater than 400 km s^{-1} , Kawka et al. 2006). LP400–22 is the only high-velocity ELM WD currently known. Understanding its origin is important for understanding the binary star evolution that results in ELM WDs. Our observations are discussed in Section 2, while an analysis of the spectroscopic data and the discovery of a companion are discussed in Section 3. The nature of the companion is discussed in Section 4.

2. OBSERVATIONS

We used the 6.5 m MMT telescope equipped with the Blue Channel Spectrograph to obtain moderate resolution spectroscopy of LP400–22 six times on UT 2008 September 23, four times on September 24, and three times on December 22. The spectrograph was operated with the 832 line mm^{-1} grating in second order, providing a wavelength coverage of 3600–4500 Å. All spectra were obtained with a $1''.0$ slit yielding a resolving power of $R = 4300$. Exposure times ranged from 5 to 10 minutes and yielded a composite spectrum with a signal-to-noise ratio $S/N > 100$ in the continuum at 4000 Å. All spectra were obtained at the parallactic angle, and comparison lamp

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Table 1
Radial Velocity Measurements for LP400–22

HJD	Heliocentric Radial Velocity (km s^{-1})
2454732.63362	-280.35 ± 5.35
2454732.63772	-296.30 ± 5.97
2454732.67339	-255.55 ± 3.63
2454732.73553	-233.37 ± 3.61
2454732.82065	-161.73 ± 5.87
2454732.90224	-100.40 ± 5.93
2454733.60017	-285.16 ± 5.46
2454733.63906	-270.94 ± 6.64
2454733.74270	-213.23 ± 3.81
2454733.90517	-104.57 ± 5.59
2454822.55410	-269.00 ± 4.65
2454822.62387	-225.91 ± 7.36
2454822.67241	-188.40 ± 5.40

exposures were obtained after every exposure. We checked the stability of the spectrograph by measuring the radial velocity of the Hg emission line at 4358.34 \AA and found it to be stable to within 3 km s^{-1} . The spectra were flux-calibrated using blue spectrophotometric standards (Massey et al. 1988).

Heliocentric radial velocities were measured using the cross-correlation package RVSAO (Kurtz & Mink 1998). We obtained preliminary velocities by cross-correlating the observations with bright WD templates of known velocity. However, greater velocity precision comes from cross-correlating LP400–22 with itself. Thus, we shifted the individual spectra to rest frame and summed them together into a high S/N template spectrum. Our final velocities come from cross-correlating the individual observations with the LP400–22 template, and are presented in Table 1. The errors in velocities are estimated from the cross-correlation peak. In order to check these error estimates, we added noise to each spectrum and performed the cross-correlation 100 times. The errors derived from this analysis are consistent with those returned by the RVSAO package cross-correlation.

Noise self-correlation is not an issue for our velocities. As a first test, we created a series of co-added templates always excluding the particular spectrum to be correlated from the co-addition. We found that these velocities are consistent with those presented in Table 1 within 1 km s^{-1} . As an additional test, we also used the best-fit WD model spectrum (see Section 3) to measure radial velocities, and found that the results are consistent within 7 km s^{-1} . Finally, an independent analysis by one of the authors found radial velocity differences of up to 8 km s^{-1} for individual spectra. Thus, the systematic errors in our measurements are less than 10 km s^{-1} ; the mean velocity difference between the analyses is $0 \pm 5 \text{ km s}^{-1}$. This gives us confidence that the velocities given in Table 1 are reliable.

3. LP400–22 AND ITS COMPANION

The radial velocity of LP400–22 varies by as much as 196 km s^{-1} between different observations, revealing the presence of a companion object. We weight each velocity by its associated error and solve for the best-fit orbit using the code of Kenyon & Garcia (1986). The heliocentric radial velocities are best fit with a circular orbit and a radial velocity amplitude $K = 118.7 \pm 14.1 \text{ km s}^{-1}$. The best-fit orbital period is 0.98776 ± 0.0001 days with spectroscopic conjunction at HJD 2454732.81 ± 0.029 . However, several aliases separated by

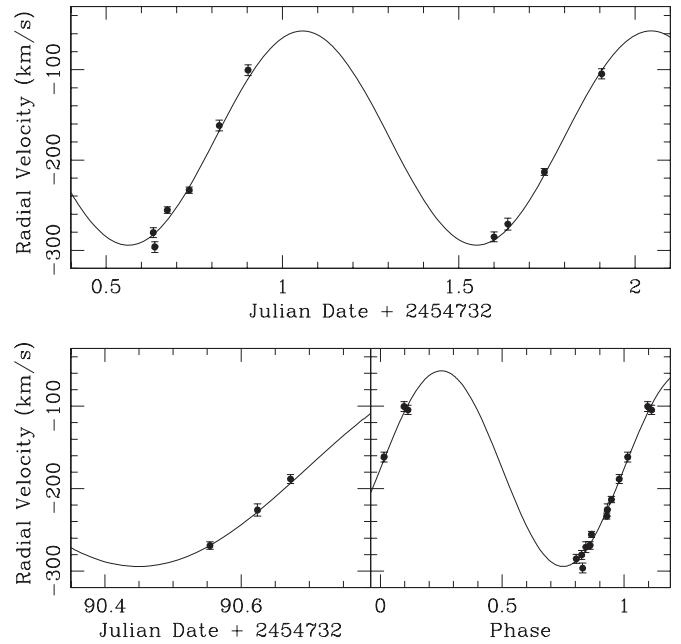


Figure 1. Radial velocities of the WD LP400–22 (black dots) observed in 2008 September (top panel) and 2008 December (bottom left panel). The bottom right panel shows all of these data points phased with the best-fit period. The solid line represents the best-fit model for a circular orbit with a radial velocity amplitude of 118.7 km s^{-1} and a period of 0.98776 day.

roughly 0.01 day, e.g., 0.9770 ± 0.0001 and 0.9988 ± 0.0001 day, are also present. Figure 1 shows the observed radial velocities and the best fit period for LP400–22. Even though we observed LP400–22 over three nights separated by 90 days, due to its nearly one day orbit, we were only able to cover half of the orbital phase. The long time baseline helps us constrain the orbital period accurately. However, the lack of full orbital coverage causes the relatively large error (12%) in the velocity semiamplitude measurement.

The discovery spectra of LP400–22 from the APO 3.5 m telescope were kindly made available to us by A. Kawka. These data consist of two exposures obtained in 2001 and have different resolution and wavelength coverage from our observations (see Kawka et al. 2006). Therefore, systematic differences in measuring the radial velocities are inevitable. Cross-correlating these two spectra with our template spectrum, we measure velocities of $-177.1 \pm 14.3 \text{ km s}^{-1}$ and $-32.2 \pm 8.4 \text{ km s}^{-1}$. Including these measurements in our orbital fits changes the orbital period slightly to 1.01 day, but with a significantly larger χ^2 . The velocities from these spectra are also consistent with the range of velocities expected from our best-fit orbital solution. We note that the choice of periods mentioned above makes negligible changes to the radial velocity semiamplitude.

We perform model fits to each individual spectrum and also to the composite spectrum using synthetic WD spectra kindly provided by D. Koester. We use the 13 individual spectra to obtain a robust estimate of the errors in our analysis. Figure 2 shows the composite spectrum and our fits using the entire spectrum and also using only the Balmer lines. A best-fit solution of $T_{\text{eff}} = 11440 \pm 70 \text{ K}$ and $\log g = 6.35 \pm 0.01$ results from the observed composite spectrum. Slight differences between the continuum level of the observations and that of the best-fit model spectrum redward of 4000 \AA show that the flux calibration was not perfect. If we normalize (continuum-correct)

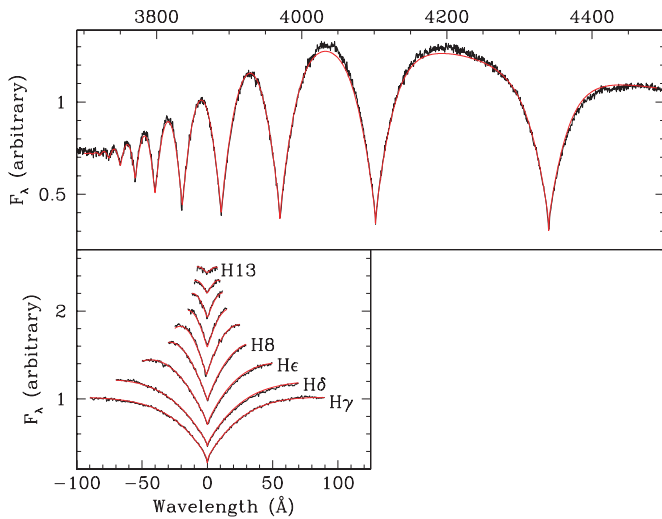


Figure 2. Spectral fits (solid lines) to the observed composite spectrum of LP400–22 (jagged lines, top panel) and to the flux-normalized line profiles (bottom panel).

the composite spectrum and fit just the Balmer lines, then we obtain $T_{\text{eff}} = 11290 \pm 50$ K and $\log g = 6.30 \pm 0.02$. Our results are consistent with each other, and also with Kawka et al.’s (2006) estimates of $T_{\text{eff}} = 11080 \pm 140$ K and $\log g = 6.32 \pm 0.08$. We adopt our best-fit solution of $T_{\text{eff}} = 11290 \pm 50$ K and $\log g = 6.30 \pm 0.02$ for the remainder of this Letter. We confirm that LP400–22 is an ELM WD.

Comparing our temperature and surface gravity measurements to Althaus et al. (2001) models shows that LP400–22 has $M \approx 0.17 M_{\odot}$. The effective temperature and surface gravity estimates for LP400–22 are slightly different than the predicted values for a $0.17 M_{\odot}$ WD (see Figure 9 in Kilic et al. 2007a). Kawka et al. (2006) used their best-fit model spectra and the mass–radius relations of Althaus et al. (2001) and Serenelli et al. (2001) to estimate an absolute magnitude of $M_V = 9.1 \pm 0.2$ mag, a distance of 430 ± 45 pc, and a WD cooling age of 500 Myr. We adopt these values for our analysis as well. Using the orbital period and the semiamplitude of the radial velocity variations, we estimate a mass function for LP400–22 of 0.171 ± 0.043 . Using $M = 0.17 M_{\odot}$ for the WD, we can set a lower limit on the mass of the companion by assuming an edge-on orbit ($\sin i = 1$), for which the companion would be a $0.37 M_{\odot}$ object at an orbital separation of $3.4 R_{\odot}$. Therefore, the companion mass is $M \geq 0.37 M_{\odot}$.

4. THE NATURE OF THE COMPANION

4.1. A Low-Mass Star

We combine the spectra near maximum blueshifted radial velocity and near minimum radial velocity into two composite spectra. If there is a contribution from a companion object, it may be visible as an asymmetry in the line profiles. We do not see any obvious asymmetries in the line profiles and conclude that our optical spectroscopy does not reveal any spectral features from a companion object.

LP400–22 has $M_V \approx M_I \approx 9.1$ mag (Kawka et al. 2006). A low-mass star companion with $M \geq 0.37 M_{\odot}$ would have $M_I < 8.8$ mag (Kroupa & Tout 1997), brighter than the low-mass WD and detectable in the *I* band. Hence, a main-sequence star companion is ruled out.

4.2. Another White Dwarf

Using the mean inclination angle for a random stellar sample, $i = 60^\circ$, we estimate that the companion mass is probably $\sim 0.48 M_{\odot}$. Kilic et al. (2007b) studied possible formation scenarios for the SDSS J0917+46 binary system involving two common envelope phases. Using the same formalism used in that study (γ -algorithm equating the angular momentum balance, Nelemans & Tout 2005), we search for possible progenitor masses and binary separations to form LP400–22 and a $0.48 M_{\odot}$ WD companion with an orbital period of 0.98776 day.

The Galactic orbit for LP400–22 is most compatible with a halo object (see Section 5). Therefore, the main-sequence age of the progenitor star is ~ 10 Gyr; the progenitor was an $\sim 1 M_{\odot}$ main-sequence star. We assume that the mass of the WD is the same as the mass of the core of the giant at the onset of the mass transfer. We assume a giant mass of $0.8\text{--}1.2 M_{\odot}$, a core mass of $0.17 M_{\odot}$, and possible WD companion masses of $0.37\text{--}1.39 M_{\odot}$. We estimate that a common envelope phase involving a $0.9 M_{\odot}$ star and a $0.48 M_{\odot}$ companion at an orbital separation of $6 R_{\odot}$ and orbital period of 1.45 days can create the LP400–22 binary observed today.

The same algorithm can be used to re-create the first common envelope phase. However, we do not find any possible solutions involving $M < 2.3 M_{\odot}$ stars⁷ if we use $\gamma = 1.5$, where γ is the rate of angular momentum loss as defined by Paczyński & Ziółkowski (1967). Nelemans & Tout (2005) found that $\gamma = 1.5$ can explain most of the systems that they studied, however, the first phase of mass transfer for individual systems could be explained by algorithms with $\gamma \approx 0.6\text{--}3$ (see their Figure 1). Assuming $\gamma = 2$ for the first common envelope phase, the LP400–22 system can be explained as the descendant of a $0.9 M_{\odot}$ star and a $1.8\text{--}2.0 M_{\odot}$ star with an orbital separation of 1.9 AU. Therefore, a likely evolutionary scenario for a WD + WD binary involving LP400–22 is $2.0 M_{\odot}$ giant + $0.9 M_{\odot}$ star at 1.9 AU \rightarrow $0.48 M_{\odot}$ WD + $0.9 M_{\odot}$ star at $6 R_{\odot}$ \rightarrow $0.48 M_{\odot}$ WD + $0.9 M_{\odot}$ giant at $6 R_{\odot}$ \rightarrow $0.48 M_{\odot}$ WD + $0.17 M_{\odot}$ WD at $3.6 R_{\odot}$.

The main-sequence lifetime of a $2 M_{\odot}$ star is less than 1 Gyr, and a $0.48 M_{\odot}$ halo WD created from such a system is ~ 10 Gyr old. According to the Bergeron et al. (1995) models, a $0.5 M_{\odot}$ CO-core WD cools down to 3250 K in 10 Gyr and it has $M_I \sim 15.4$ mag. This companion is several orders of magnitude fainter than the $0.17 M_{\odot}$ WD observed today, and therefore the lack of evidence of a companion in the optical photometry is consistent with this formation scenario.

4.3. A Neutron Star

If the orbital inclination angle of the LP400–22 binary system is less than 32° , the companion mass is $\geq 1.4 M_{\odot}$, consistent with a neutron star. Given the observational connection between low-mass WDs and MSPs, there have been several attempts at detecting MSP companions to the newly discovered low-mass WDs. Agüeros et al. (2009) conducted a search for pulsar companions to 15 low-mass WDs spectroscopically identified in the SDSS at 820 MHz with the NRAO Green Bank Telescope. However, no convincing pulsar signal was detected in their data, and they conclude that the probability that the companion to a given low-mass WD is a MSP is $< 10_{-2}^{+4}\%$. In addition, the

⁷ This limit is set by the fact that more massive stars do not form degenerate helium cores and that a common envelope phase with a more massive giant would end up in a merger and not in a binary system (Nelemans et al. 2000).

probability of observing a binary system at an angle less than 32° is only 15%. We require radio and X-ray observations of LP400–22 to put constraints on a possible pulsar companion (M. A. Agüeros et al., in preparation).

5. DISCUSSION

Our radial velocity measurements of LP400–22 show that it is in a binary system with an orbital period of 0.98776 day. Short period binaries may merge within a Hubble time by losing angular momentum through gravitational radiation. However, the merger time for the LP400–22 binary is longer than 230 Gyr for either a WD or a neutron star companion.

At a Galactic latitude of -30.6° , LP400–22 is ≈ 200 pc below the plane. The systemic radial velocity of the binary system is -175.7 ± 11.4 km s $^{-1}$, and the proper motion is $(\mu_\alpha \cos \delta, \mu_\delta) = (198, 53$ mas yr $^{-1}$; Lépine & Shara 2005). The velocity components⁸ with respect to the local standard of rest as defined by Hogg et al. (2005) are $U = -396 \pm 43$, $V = -195 \pm 15$, and $W = -27 \pm 19$ km s $^{-1}$. Clearly, LP400–22 is not a disk star. In the Galactic rest frame its total velocity is 398 ± 50 km s $^{-1}$. This is slightly lower than the canonical escape velocity of $500\text{--}550$ km s $^{-1}$ in the solar neighborhood (Carney et al. 1988; Smith et al. 2007).

For comparison, halo stars within 1 kpc of the Galactic plane have typical velocities of $U = -17 \pm 141$, $V = -187 \pm 106$, and $W = -5 \pm 94$ km s $^{-1}$ (Chiba & Beers 2000). Thus, LP400–22’s U velocity makes it an outlier among halo stars. There is only one star in the Chiba & Beers (2000) study, –29 201W1, that has UVW velocities consistent with those of LP400–22 within 2σ . This star demonstrates that stars with similar kinematics to LP400–22 do exist, but comprise only 0.1% of nearby metal-poor stars in the Chiba & Beers (2000) sample. We now explore whether LP400–22 is more plausibly explained as a disk runaway or a Galactic center ejection.

Runaway disk stars are explained by velocity kicks from 3- or 4-body dynamical interactions or from binary companions that explode as supernovae (SNe). Depending on the orbital separation and binary mass fraction, a SN explosion may or may not disrupt the binary system. If the companion to LP400–22 is a neutron star, it could be responsible for the observed high velocity of the system. However, detailed binary population synthesis calculations of runaway stars by Portegies Zwart (2000) show that less than 1% of runaways receive velocity kicks in excess of 200 km s $^{-1}$. Known low-mass WD + MSP systems can be used to test the SN kick scenario. We estimate that the PSR J1012+5307 and PSR J1911–5958A binary systems have total velocities ≤ 90 km s $^{-1}$, based on the radial and tangential velocity estimates by Lorimer et al. (1995), Bassa et al. (2006), and Corongiu et al. (2006). This comparison shows that LP400–22 is unique in its large space velocity, and the SN kick scenario is unlikely to explain it.

Justham et al. (2009) recently suggested that single runaway WDs may form from SNe Ia in short period (~ 1 hr) binary systems. Since we now know that LP400–22 is a binary with an almost one day period, the SNe Ia mechanism is ruled out for this system.

Figure 3 plots the Galactic orbit of LP400–22 for the past 1 Gyr, in a static disk–halo–bulge potential (Kenyon et al. 2008). Given its relatively low W velocity, LP400–22 stays within 10 kpc of the Galactic plane. The large U velocity causes it to

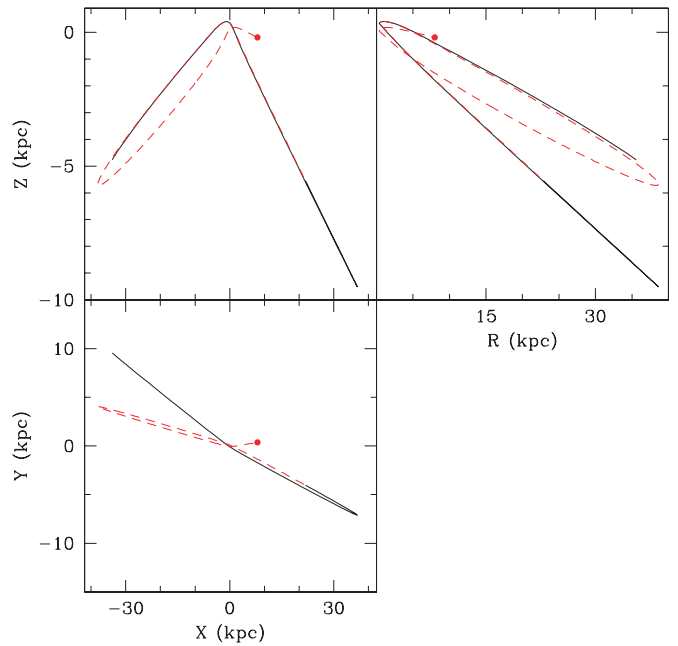


Figure 3. Galactic orbit of LP400–22 for the past 1 Gyr. The orbital motion since LP400–22 became a WD (500 Myr ago) is shown as a dashed line. The current position of the WD is marked with a dot.

move mostly in the radial direction, and its closest approach to the Galactic center occurs at a distance of $R \approx 270$ pc. Given the uncertainties in the measured parameters, we estimate that the last pericenter passage occurred around 16 Myr ago with a 0.1% chance that LP400–22 passed within 10 pc of the Galactic center. Recent discoveries of unbound hypervelocity stars in the Galaxy suggest that the extreme velocities of these stars come from dynamical interactions with the massive black hole in the Galactic center (Brown et al. 2009). However, massive black hole ejection mechanisms (Hills 1988; Yu & Tremaine 2003) are much more likely to eject single stars than binaries (Lu et al. 2007; Perets 2008, 2009), as most of the binaries are not expected to survive close to the massive black hole in the Galactic center. Tidal disruption of a hierarchical triple star system by a central massive black hole could, in principle, lead to the ejection of a close binary. Lu et al. (2007) find that the typical ejection speed of such a binary would be 400 km s $^{-1}$. However, all things considered, LP400–22 is most likely a halo binary star system with an unusual orbit.

6. CONCLUSIONS

The runaway WD LP400–22 has a radial velocity companion. The optical photometry and the orbital parameters of the system rule out a low-mass main-sequence star companion. Although a neutron star companion cannot be ruled out, the most likely companion is another WD. An SN kick or a Galactic center ejection is unlikely to explain the runaway nature of LP400–22. We suggest that LP400–22 may belong to a small sample of halo WDs with unusual orbits.

Excluding the two MSP systems, LP400–22 is only the second ELM WD studied for optical radial velocity variations. Both LP400–22 and SDSS J0917+46 show radial velocity variations due to compact companions, supporting the binary formation scenario for ELM WDs. A radial velocity follow-up survey of the other ELM WDs found in the SDSS is currently underway at the MMT.

⁸ The velocity components U , V , and W are directed to the Galactic center, rotation direction, and north Galactic pole, respectively.

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REFERENCES

- Agüeros, M. A., Camillo, F., Silvestri, N. M., Kleinman, S. J., Anderson, S. F., & Liebert, J. W. 2009, *ApJ*, in press
- Althaus, L. G., Serenelli, A. M., & Benvenuto, O. G. 2001, *MNRAS*, **323**, 471
- Bassa, C. G., van Kerkwijk, M. H., Koester, D., & Verbunt, F. 2006, *A&A*, **456**, 295
- Bergeron, P., Saumon, D., & Wesemael, F. 1995, *ApJ*, **443**, 764
- Brown, W. R., Geller, M. J., & Kenyon, S. J. 2009, *ApJ*, **690**, 1639
- Carney, B. W., Laird, J. B., & Latham, D. W. 1988, *AJ*, **96**, 560
- Chiba, M., & Beers, T. C. 2000, *AJ*, **119**, 2843
- Corongiu, A., Possenti, A., Lyne, A. G., Manchester, R. N., Camilo, F., D'Amico, N., & Sarkissian, J. M. 2006, *ApJ*, **653**, 1417
- Eisenstein, D. J., et al. 2006, *ApJS*, **167**, 40
- Hills, J. G. 1988, *Nature*, **331**, 687
- Hogg, D. W., Blanton, M. R., Roweis, S. T., & Johnston, K. V. 2005, *ApJ*, **629**, 268
- Justham, S., Wolf, C., Podsiadlowski, P., & Han, Z. 2009, *A&A*, **493**, 1081
- Kawka, A., Vennes, S., Oswalt, T. D., Smith, J. A., & Silvestri, N. M. 2006, *ApJ*, **643**, L123
- Kenyon, S. J., Bromley, B. C., Geller, M. J., & Brown, W. R. 2008, *ApJ*, **680**, 312
- Kenyon, S. J., & Garcia, M. R. 1986, *AJ*, **91**, 125
- Kepler, S. O., Kleinman, S. J., Nitta, A., Koester, D., Castanheira, B. G., Giovannini, O., Costa, A. F. M., & Althaus, L. 2007, *MNRAS*, **375**, 1315
- Kilic, M., Allende Prieto, C., Brown, W. R., & Koester, D. 2007a, *ApJ*, **660**, 1451
- Kilic, M., Brown, W. R., Allende Prieto, C., Pinsonneault, M. H., & Kenyon, S. J. 2007b, *ApJ*, **664**, 1088
- Kilic, M., Stanek, K. Z., & Pinsonneault, M. H. 2007c, *ApJ*, **671**, 761
- Kroupa, P., & Tout, C. A. 1997, *MNRAS*, **287**, 402
- Kurtz, M. J., & Mink, D. J. 1998, *PASP*, **110**, 934
- Lépine, S., & Shara, M. M. 2005, *AJ*, **129**, 1483
- Liebert, J., Bergeron, P., Eisenstein, D., Harris, H. C., Kleinman, S. J., Nitta, A., & Krzesinski, J. 2004, *ApJ*, **606**, L147
- Liebert, J., Bergeron, P., & Holberg, J. B. 2005, *ApJS*, **156**, 47
- Lorimer, D. R., Lyne, A. G., Festin, L., & Nicastro, L. 1995, *Nature*, **376**, 393
- Lu, Y., Yu, Q., & Lin, D. N. C. 2007, *ApJ*, **666**, L89
- Marsh, T. R., Dhillon, V. S., & Duck, S. R. 1995, *MNRAS*, **275**, 828
- Massey, P., Strobel, K., Barnes, J. V., & Anderson, E. 1988, *ApJ*, **328**, 315
- Nelemans, G., & Tout, C. A. 2005, *MNRAS*, **356**, 753
- Nelemans, G., Verbunt, F., Yungelson, L. R., & Portegies Zwart, S. F. 2000, *A&A*, **360**, 1011
- Paczynski, B., & Ziolkowski, J. 1967, *Acta Astron.*, **17**, 7
- Perets, H. B. 2008, *ApJ*, submitted (arXiv:0802.1004)
- Perets, H. B. 2009, *ApJ*, **690**, 795
- Portegies Zwart, S. F. 2000, *ApJ*, **544**, 437
- Serenelli, A. M., Althaus, L. G., Rohmann, R. D., & Benvenuto, O. G. 2001, *MNRAS*, **325**, 607
- Smith, M. C., et al. 2007, *MNRAS*, **379**, 755
- van Kerkwijk, M. H., Bassa, C. G., Jacoby, B. A., & Jonker, P. G. 2005, in Proc. ASP Conf. Ser. 328, Binary Radio Pulsars, ed. F. A. Rasio & I. H. Stairs (San Francisco, CA: ASP), 357
- Yu, Q., & Tremaine, S. 2003, *ApJ*, **599**, 1129