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Adela Kawka
Czech Academy of Sciences

Stephane Vennes
Florida Institute of Technology

Terry D. Oswalt
Florida Institute of Technology, oswaltt1@erau.edu

J. Allyn Smith
Florida Institute of Technology

Nicole M. Silvestri
University of Washington

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LP 400-22, A VERY LOW MASS AND HIGH-VELOCITY WHITE DWARF

Adela Kawka
Astronomický ústav, AV ČR, Fričova 298, 25165 Ondřejov, Czech Republic; kawka@sunstel.asu.cas.cz
Stéphane Vennes, Terry D. Oswalt, and J. Allyn Smith[1]
Department of Physics and Space Sciences, Florida Institute of Technology, 150 West University Boulevard, Melbourne, FL 32901-6975; svennes@fit.edu, toswalt@fit.edu, jasmith@astro.fit.edu
and
Nicole M. Silvestri
Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195; nms@astro.washington.edu
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ABSTRACT

We report the identification of LP 400-22 (WD 2234+222) as a very low mass and high-velocity white dwarf. The ultraviolet *GALEX* and optical photometric colors and a spectral line analysis of LP 400-22 show this star to have an effective temperature of 11,080 ± 140 K and a surface gravity of $\log g = 6.32 \pm 0.08$. Therefore, this is a helium-core white dwarf with a mass of 0.17 $M_\odot$. The tangential velocity of this white dwarf is 414 ± 43 km s^{-1}, making it one of the fastest moving white dwarfs known. We discuss probable evolutionary scenarios for this remarkable object.

Subject headings: stars: atmospheres — stars: individual (LP 400-22) — white dwarfs

1. INTRODUCTION

The vast majority of white dwarfs evolve from normal main-sequence stars following normal evolutionary processes. However, ultramassive (>1.1 $M_\odot$) and inframassive (<0.40 $M_\odot$) white dwarfs require special evolutionary paths. The formation of low-mass helium white dwarfs ($M_{\rm WD} \lesssim 0.4\ M_\odot$) has been shown to be the result of close binary evolution (Iben & Tutukov 1986 and references therein). Indeed, the Galaxy is not old enough for these objects to have formed through single-star evolution. The general evolutionary scenario for the formation of low-mass helium white dwarfs is that the companion stripped the white dwarf of its envelope before completing its red giant evolution (Kippenhahn et al. 1967).

Recently, several very low mass white dwarfs ($M_{\rm WD} \lesssim 0.2\ M_\odot$) have been discovered as companions to pulsars (van Kerkwijk et al. 2005). The orbital periods vary from a few hours to several years. The masses of some of these white dwarfs may be determined from the Shapiro delay of radio pulses provided that the system is nearly edge-on (Löhmer et al. 2005). For example, Jacoby et al. (2003) deduced a mass of 0.20 $M_\odot$ for the companion of PSR J1909−3744, and they obtained a spectrum that confirmed, at least qualitatively, the presence of a low-mass DA white dwarf. In addition, the masses of the companions to PSR J1012+5307 and PSR J1911−5958 were determined spectroscopically to be 0.16 $M_\odot$ (van Kerkwijk et al. 1996; Callanan et al. 1998) and 0.18 $M_\odot$ (Bassa et al. 2006), respectively. Finally, several low-mass white dwarf candidates were found in the Sloan Digital Sky Survey (Kleinman et al. 2004). Liebert et al. (2004) analyzed the brightest star in the sample, SDSS J123410.37−022802.9, and showed that it has a mass of ∼0.18 $M_\odot$ and that it does not have an obvious neutron star companion.

In this Letter, we report the identification of a high-velocity white dwarf with a very low mass, LP 400-22 (WD 2234+222,[2] NLTT 54331). Our photometric and spectroscopic observations are presented in §§ 2.1 and 2.2, respectively. We derive the stellar parameters in § 3 and discuss our results in § 4.

2. OBSERVATIONS

LP 400-22 was spectroscopically identified as a white dwarf as part of a survey of common proper-motion binaries with suspected white dwarf components (Oswalt et al. 1993). We obtained additional high-resolution optical spectra (Silvestri 2002) as well as new optical photometry (Smith 1997) as part of the same project. More recently, LP 400-22 was observed during the *Galaxy Evolution Explorer* (*GALEX*) all-sky survey.

2.1. *Photometry*

The *BVRI* photometry for LP 400-21/22 were obtained with the 2.1 m telescope at Kitt Peak National Observatory (KPNO) on 1995 July 5 UT. A Tek1K CCD (with 24 μm pixels) operating at the Cassegrain focus was used, providing 0″.305 pixel^{-1} and a 5′.2 field of view. The data for LP 400-21/22 were obtained under photometric conditions. Standard stars for this program were chosen from Landolt (1992).

We obtained ultraviolet (UV) photometry from the *GALEX* all-sky survey.[3] *GALEX* provides photometry in two bands, FUV and NUV, that are based on the AB system (Morrissey et al. 2005; Oke & Gunn 1983). The bandwidth of FUV is 1344–1786 Å with an effective wavelength of 1528 Å. The bandwidth of NUV is 1771–2831 Å with an effective wavelength of 2271 Å.

Table 1 presents the optical and ultraviolet photometry, and Figure 1 shows the energy distribution compared to a synthetic spectrum.

2.2. *Spectroscopy*

We obtained a low-resolution spectrum of LP 400-22 using the Ritchey-Chrétien spectrograph attached to the 4 m telescope at KPNO on 1988 October 6. The BL250 grating (158 lines mm^{-1}) was used to obtain a spectral range of

[1] Visiting Astronomer, KPNO/NOAO, which is operated by AURA, Inc., under cooperative agreement with the NSF.
[2] Online at http://www.astronomy.villanova.edu/WDCatalog/index.html.
[3] Available from http://galex.stsci.edu/GR1/.

TABLE 1
PHOTOMETRY

Band (mag)	LP 400-22	LP 400-21
FUV[a]	18.38 ± 0.09	...
	18.18 ± 0.08	...
NUV[a]	18.19 ± 0.05	...
	18.14 ± 0.04	...
B	17.338 ± 0.025	18.742 ± 0.025
V	17.219 ± 0.021	17.177 ± 0.021
R	17.202 ± 0.023	15.933 ± 0.023
I	17.210 ± 0.024	14.340 ± 0.023

[a] The mean of these values is used in this Letter.

3500–6200 Å with a dispersion of 5.52 Å pixel^{-1} and a resolution of 14 Å.

LP 400-22 was reobserved using the Dual Imaging Spectrogram (DIS) attached to the 3.5 m telescope at the Apache Point Observatory (APO) on 2001 July 10 and October 14. The 1200 lines mm^{-1} grating was used to obtain a spectral range of 3800–4600 Å with a dispersion of 1.6 Å pixel^{-1}, and the 830.8 lines mm^{-1} grating was used to obtain a spectral range of 6180–7210 Å with a dispersion of 1.3 Å pixel^{-1}. A 1''.5 slit was used to obtain a spectral resolution of ∼2 Å in the blue and ∼2.6 Å in the red.

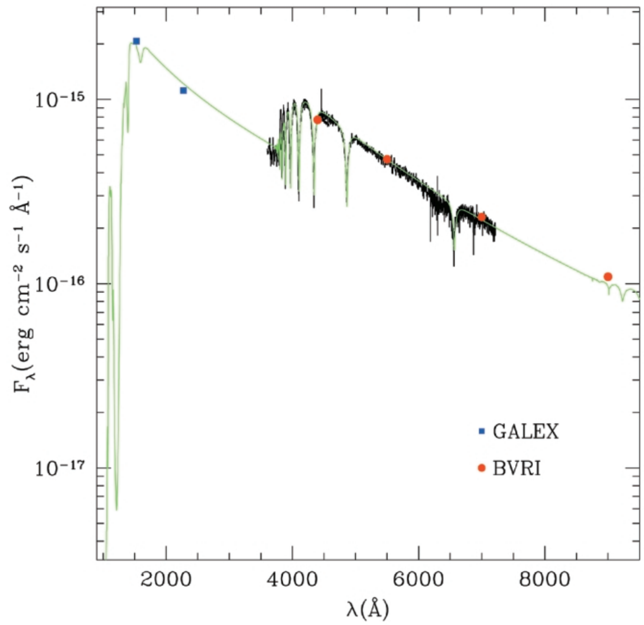

FIG. 1.—Energy distribution of LP 400-22 combining all available data compared to our H-rich model spectrum at $T_{\rm eff}$ = 11,000 K and log g = 6.50 (see § 3).

3. DETERMINING THE PARAMETERS

In our analysis of LP 400-22, we used a grid of computed pure-hydrogen LTE plane-parallel models (see Kawka & Vennes 2006 and references therein for details). The grid of models extends from $T_{\rm eff}$ = 7000 to 16,000 K (in steps of 1000 K), from 18,000 to 32,000 K (in steps of 2000 K), and from 36,000 to 84,000 K (in steps of 4000 K) at log g = 6.0–9.5 (in steps of 0.25 dex). All our log g values are in cgs units. We also prepared corresponding grids of synthetic spectra, of which one includes the effect of Lyα satellites (Allard & Koester 1992) and the other excludes that effect.

3.1. *Photometry*

Using our spectral grid, we have calculated synthetic optical (*BVRI*) and ultraviolet (FUV/NUV) colors. Figure 2 shows the observed photometric colors ($V-$FUV vs. FUV $-$ NUV and $B-V$ vs. $V-R$) of LP 400-22 compared to synthetic white

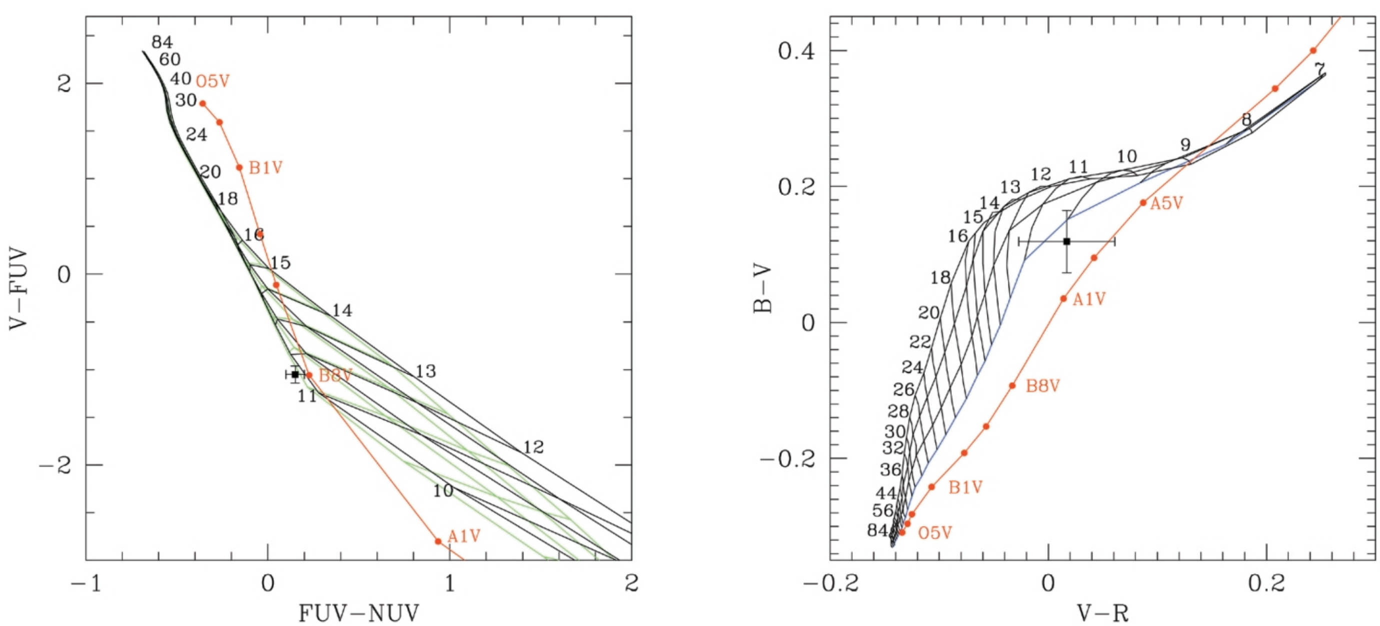

FIG. 2.—*GALEX* $V-$FUV vs. FUV $-$ NUV (*left*) and optical $B-V$ vs. $V-R$ (*right*) diagrams showing the position of LP 400-22 compared to the DA white dwarf sequence and the main sequence (in red). The effective temperatures are indicated in units of 1000 K, and the log g = 6.0, 7.0, 8.0, and 9.0 (*from bottom to top*). In the optical diagram, log g = 6.0 is indicated by the blue line. In the UV-optical diagram, the grid shown in black includes the Lyα satellite, and the grid in green does not.

dwarf and main-sequence colors. We used Kurucz synthetic spectra (Kurucz 1993) to calculate our main-sequence colors.

In the UV-optical diagram ($V-$ FUV/FUV $-$ NUV) of Figure 2, we show two sets of white dwarf synthetic colors. The grid shown in black includes the effect of Lyα satellites (Allard & Koester 1992), and the grid shown in green excludes them. A comparison of the two grids shows the significant effect that the Lyα satellites have on the UV colors at $T_{\rm eff} < 13{,}000$ K. Comparing the UV-optical photometry of LP 400-22 to the white dwarf grid, a low surface gravity $\log g \sim 6$ and an effective temperature of $\sim$11,000 K are implied. The optical diagram ($B-V$/$V-R$) in Figure 2 confirms the white dwarf temperature of 11,000 K and the low surface gravity.

However, when comparing the photometry to main-sequence colors, a A3 V spectral type is implied in the optical, and a B8 V spectral type in the ultraviolet. Therefore, the data are incompatible with main-sequence colors. Optical and UV colors are useful to distinguish white dwarfs from main-sequence stars.

3.2. *Spectroscopy*

The Balmer lines of LP 400-22 were analyzed in all three available spectra using a χ^2 minimization technique. The quoted uncertainties are statistical only (1 σ). The Balmer lines (Hβ–H9) in the KPNO spectrum were fitted with model spectra that were smoothed to the instrumental resolution of 14 Å, to obtain $T_{\rm eff} = 11{,}000 \pm 350$ K and $\log g = 6.48 \pm 0.27$. For the two high-resolution APO spectra, we fitted Hα and Hγ to H9 with model spectra, to obtain $T_{\rm eff} = 11{,}060 \pm 180$ K and $11{,}160 \pm 250$ K, and $\log g = 6.46 \pm 0.13$ and 6.22 ± 0.10. The synthetic spectra used in the analysis of the APO spectra were smoothed with a Gaussian profile to the instrumental resolution of 2 Å. Note that the discrepancy in the surface gravities from the two APO spectra are most likely the result of uncertainties in the flux calibration around the higher Balmer lines. The Balmer line fit of the KPNO spectrum is shown in Figure 3. These measurements clearly confirm that LP 400-22 is a white dwarf with a low surface gravity. The calculated weighted averages of the temperature and surface gravity are $T_{\rm eff} = 11{,}080 \pm 140$ K and $\log g = 6.32 \pm 0.08$.

We used the evolutionary tracks for helium-core white dwarfs of Althaus et al. (2001) and Serenelli et al. (2001) to determine a mass of $0.17 \pm 0.01\ M_\odot$ and a cooling age of $(5 \pm 1) \times 10^8$ yr. Note that the cooling age of the white dwarf is sensitive to the mass of the hydrogen envelope that is left before the white dwarf enters the final cooling track (see Althaus et al. 2001 and references therein). Residual H burning in a thick H envelope causes the white dwarf to cool slower than a white dwarf with a thin H envelope.

The temperature of 11,080 K places LP 400-22 near the blue edge of the ZZ Ceti instability strip (Gianninas et al. 2005). Given the lack of time coverage in our data, we cannot state whether the star is variable or not. Time-series photometry is required to explore variability and place constraints on the blue edge of the instability strip at the low-mass range.

4. DISCUSSION

LP 400-22 was listed in the New Luyten Two-Tenths (NLTT) catalog (Luyten 1979) to have a common proper-motion companion (LP 400-21) 338″ away. Recently, Salim & Gould (2003) have revised the coordinates and proper motions of most stars in the NLTT catalog by cross-correlating the catalog with the Two Micron All Sky Survey (2MASS) and the USNO-A catalogs. LP 400-22 was not detected in 2MASS, and therefore they relisted Luyten's measurement of the proper motion. They listed the proper motion of LP 400-22 to be $\mu_\alpha = 0\farcs1950 \pm 0\farcs0200$ yr^{-1} and $\mu_\delta = 0\farcs0563 \pm 0\farcs0200$ yr^{-1}. For LP 400-21, they measured a proper motion of $\mu_\alpha = 0\farcs2158 \pm 0\farcs0055$ yr^{-1} and $\mu_\delta = 0\farcs0283 \pm 0\farcs0055$ yr^{-1}. These proper-motion measurements agree within 2 σ, and on this basis the two stars appear to be a common proper-motion binary. However, similar measurements were reported by Lépine & Shara (2005), i.e., $\mu_\alpha = 0\farcs198$ yr^{-1} and $\mu_\delta = 0\farcs053$ yr^{-1} for LP 400-22, and $\mu_\alpha = 0\farcs228$ yr^{-1} $\mu_\delta = 0\farcs020$ yr^{-1} for LP 400-21. The quoted uncertainties in the Lépine & Shara (2005) measurements are $\sim 0\farcs007$ yr^{-1}, and therefore the diverging proper motions of the two stars appear to exclude a physical association. Another way to check whether the stars are a physical binary is to determine the distance of each star.

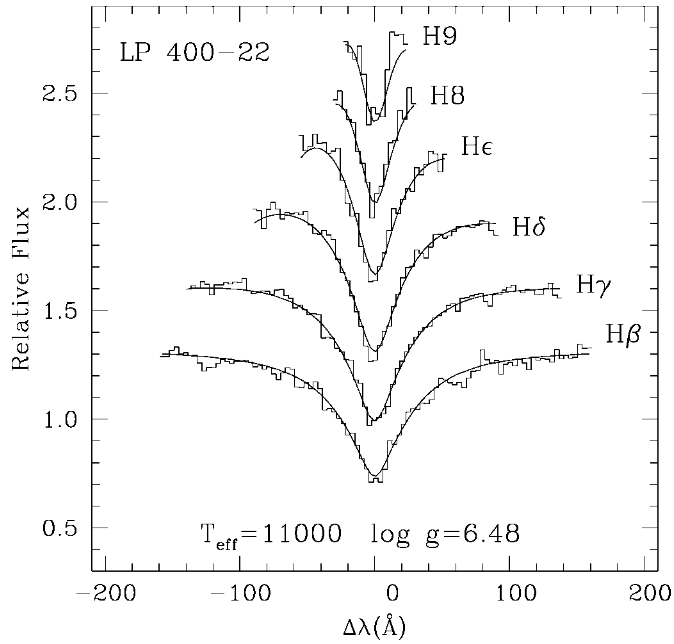

FIG. 3.—Spectral fit of the Balmer lines (Hβ–H9) of the KPNO spectrum of LP 400-22.

To estimate the distance, we calculated an absolute magnitude of $M_V = 9.1 \pm 0.2$ mag for LP 400-22 and a distance modulus of $(V - M_V) = 8.2$ mag. This places the white dwarf at a distance of 430 ± 45 pc. Note that the Galactic extinction for this object is low and that its effect was not included. Silvestri et al. (2005) classified LP 400-21 as a dM4.5e, and using the M_V/$V-I$ relation from Reid & Gizis (1997), we estimate the absolute magnitude of the red dwarf as 12.7 mag. The apparent V magnitude for LP 400-21 is $V = 17.177 \pm 0.021$ mag, and therefore the red dwarf is at a distance of $\sim$80 pc. Reid & Gizis (1997) note a scatter of values about the relation with $\sigma = 0.46$. Even if we consider LP 400-21 at the extrema of this dispersion, it would place it at a distance of only $\sim$100 pc. The large distance discrepancy makes LP 400-22/21 a coincidental pair rather then a wide binary as has been thought based on their proper motion alone.

The large distance and high proper motion of LP 400-22 imply a large tangential velocity of 414 ± 43 km s^{-1}. Only a few white dwarfs are known to have $v_{\rm tan} > 350$ km s^{-1}, with most of these having halo space velocities (Bergeron et al. 2005). In order to obtain the (U, V, W)-space velocity components for LP 400-22, we measured the radial velocity of the white dwarf using Hα in the APO high-dispersion spectra to obtain a heliocentric value of -50 ± 20 km s^{-1}, which is different from the velocity measured for the red dwarf (7.3 km s^{-1}) by Silvestri et al. (2002). We calculated U, V, W for LP 400-22 using Johnson & Soderblom (1987) to obtain $U = -388 \pm 43$, $V = -81 \pm 22$, $W = -83 \pm 22$ km s^{-1}. These velocity components do not agree with either disk or halo populations (Chiba & Beers 2000) and suggest a different origin for its peculiar motion. The Galactic orbit for LP 400-22 should be calculated.

Most white dwarfs with $M < 0.2\ M_\odot$ are companions to pulsars. We searched for radio sources in the vicinity of LP 400-22 using VizieR,[4] and the nearest was that of the galaxy KUG 2234+223 ~7′.5 away. Therefore, if LP 400-22 is a companion to a neutron star, then it is probably a dead pulsar. Another possibility is that LP 400-22 has a very cool companion, which should be detectable as infrared excess. However, LP 400-22 was not detected by 2MASS. The two high-dispersion velocity measurements agree within error bars. However, a series of radial velocity measurements should be obtained to establish whether or not LP 400-22 is in a close binary system.

Yet another possibility for the origin of LP 400-22 is that it may have once been in a close double-degenerate binary, where the companion has gone through a supernova event that disrupted the binary, losing the remnant of the donor star with a high velocity and a low mass (Hansen 2003).

5. SUMMARY

We have demonstrated that LP 400-22 is a high-velocity white dwarf with a very low mass ($M = 0.17\ M_\odot$) and a temperature of 11,080 K. Table 2 summarizes the properties of LP 400-22.

[4] See http://vizier.u-strasbg.fr/viz-bin/VizieR.

TABLE 2

LP 400-22 PARAMETERS

Parameter	Measurement	Refs.
Effective temperature	11,080 ± 140 K	1
Surface gravity	6.32 ± 0.08	1
Mass	$0.17 \pm 0.01\ M_\odot$	1
M_V	9.1 ± 0.2 mag	1
Distance	430 ± 45 pc	1
Proper motion	$\mu = 0''.203$ yr^{-1}, $0''.205$ yr^{-1}	2, 3
	$\theta = 73^\circ.9$, $75^\circ.0$	2, 3
Kinematics	$U = -388 \pm 43$ km s^{-1}	1
	$V = -81 \pm 22$ km s^{-1}	1
	$W = -83 \pm 22$ km s^{-1}	1

REFERENCES.—(1) This work; (2) Salim & Gould 2003 and Luyten 1979; (3) Lépine & Shara (2005).

Since white dwarfs with masses below 0.4 $M_\odot$ must have been formed in close binary systems, radial velocity measurements and infrared photometry are required to determine whether LP 400-22 has a close companion. On the other hand, a lack of radial velocity variations would indicate that LP 400-22 lost its close massive companion following a Type Ia supernova event.

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