An ancient double degenerate merger in the Milky Way halo

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ABSTRACT

We present an analysis and re-appraisal of the massive, carbon-enriched (DQ) white dwarf (WD) LP 93-21. Its high mass (∼1.3 M⊙) and membership to the class of warm DQ WDs, combined with its peculiar halo kinematics suggest that this object is the product of an ancient stellar merger event, most likely that of two WDs. Furthermore, the kinematics places this object on a highly retrograde orbit driven by the accretion of a dwarf galaxy onto the Milky Way that occurred at a red shift greater than 1.5. As the product of a stellar merger LP 93-21 is probably representative of the whole class of warm/hot DQ WDs.

Key words: stars: individual: LP 93-21 – white dwarfs – stars: kinematics and dynamics – Galaxy: halo – Galaxy: kinematics and dynamics – Galaxy: structure

1 INTRODUCTION

White dwarfs are the final stage in the life of a majority of stars, and many are found in close binary systems, either in double degenerate binaries or as a companion to a main-sequence star. However, the fraction of binaries in the WD population is only about 25% which is significantly lower than the fraction of about 50% of binaries among main-sequence stars (Ferrario 2012; Toonen et al. 2017) thus indicating that there should be a population of single WDs that formed through merging events described by, e.g., Lorén-Aguilar, Isern & García-Berro (2009); Briggs et al. (2015).

The presence of an excess of massive WDs in the local population was first uncovered in the Extreme Ultraviolet (EUVE) survey of hot WDs (Vennes et al. 1997; Vennes 1999). Recently, using Gaia parallax measurements and Sloan Digital Sky Survey (SDSS) photometric measurements, Kilic et al. (2018) found that the WD mass distribution is bifurcated and that the massive WD peak near 0.8 M⊙ and the high-mass tail beyond harbour WDs that formed in mergers. However, Bergeron et al. (2019) suggested that some of these objects could have a normal mass (∼0.6 M⊙) but with a mixed H/He atmosphere. Further observations would be required to disentangle the effects of mass and chemical composition.

We expect that WDs that are the products of mergers should have properties that differ from those originating from single star evolution. For instance, mergers are likely to be massive, have short rotation periods, and some could be magnetic. In fact, a significant fraction of WDs possess a magnetic field, although the incidence of magnetism varies among the various spectral classes (Kawka et al. 2019). One group of WDs, the rare hot and carbon-rich DQs, have an exceptionally high incidence of magnetism (Dufour et al. 2013). They are also fast rotators, with periods ranging from a few minutes to a couple of days (Dunlap & Clemens 2015; Williams et al. 2016), and have an average mass higher than that of the general WD population. Recently, Coutu et al. (2019) showed that there is a population of massive, warm (16 000 ≤ T eff ≤ 16 000 K) DQs and suggested that these may be the descendants of hot DQs.

The case of the warm DQ LP 93-21 merits further attention. This object was first identified as a high proper motion star in the Luyten Palomar survey and as a WD candidate by Luyten (1968). Sandage (1968) first discovered that LP 93-21 could have a retrograde orbit. The first spectra were obtained by Liebert & Strittmatter (1977) and Greenstein et al. (1977). The latter also found that LP 93-21 is likely to have a retrograde orbit and is more massive than the average WD. A trigonometric parallax of π = 0.0114 ± 0.0054 arcsec was obtained by Harrington et al. (1985), but the uncertainty was too large to place a useful constraint on its mass. The first modelling of its spectrum was performed by Bues (1979), who measured T eff = 8500 K, log g = 7.8 and log C/He = −2.9, resulting in a relatively low mass (∼0.5 M⊙). However, the recent Gaia parallax measurement firmly established its very high mass (∼1.1 M⊙, Leggett et al. 2018; Kilic et al. 2019).

Recently, LP 93-21 was reported as a hyper-runaway WD and Type Iax supernova (SN Iax) remnant candidate by Ruffini & Casey (2019). They proposed that LP 93-21 is unbound to the Milky Way and that its large velocity and carbon-rich surface occurred in the aftermath of a partial core deflagration, similar to events leading to the formation of the hyper-velocity and low mass WD LP 40-365 (Vennes et al. 2017). However, unlike LP 40-365 which has a very peculiar oxygen/neon-rich atmosphere devoid of traces of hydrogen or helium, LP 93-21 is helium dominated with a large quantity of carbon mixed in the convective envelope (Leggett et al. 2018; Kilic et al. 2019) but without the expected products of carbon burning.

In this paper we show that the stellar properties and kinematics of LP 93-21 are more consistent with this star being the product
of a stellar merger. We revisited SDSS spectroscopy of known DQ WDs (Section 2) and extracted reliable stellar parameters and radial velocity measurements (Sections 2.1 and 2.2). In particular, we pay close attention to the density and temperature in the line forming region and their effect on the carbon line spectrum. We discuss the revised kinematics (Section 2.3) in the context of an ancient region and their effect on the carbon line spectrum. We discuss velocity measurements (Sections 2.1 and 2.2). In particular, we pay attention to the density and temperature in the line forming region and their effect on the carbon line spectrum.

## 2 OBSERVATION AND ANALYSIS

We have assembled the known population of DQ WDs and extracted astrometric and photometric measurements from the second data release of Gaia (Gaia Collaboration, et al. 2018). We also collected spectroscopic and photometric measurements of LP 93-21 and related stars from the SDSS (Aguado et al. 2019). Table 1 lists astrometric and photometric data for LP 93-21 in Section 3.2 and we summarize our results and conclude in Section 4.

### 2.1 Stellar parameters: LP 93-21

Kilic et al. (2019) and Leggett et al. (2018) determined effective temperatures of 8690 ± 120 K and 9730 ± 49 K, respectively and high masses of 1.03 ± 0.02 M⊙ and 1.14 ± 0.01 M⊙, respectively. We have re-analyzed the SDSS spectrum and Gaia parallax of LP 93-21 using models described in Vennes & Kawka (2012) and obtained stellar parameters entirely consistent with the above results. Details of the models will be described in a forthcoming paper (Kawka et al. 2019, in preparation). Table 2 lists the stellar properties of LP 93-21 including the Gaia distance measurement.

### 2.2 The carbon line spectrum

We examined the SDSS spectra of a sample of nine warm, massive DQ WDs (10–16×10^3 K, M > 0.8 M⊙) including LP 93-21. These objects have a higher carbon abundance (log C/He ≈ −4 to −2) and a higher mass than normal DQ WDs (Coutu et al. 2019), but they are somewhat cooler than the hot DQ WDs described by Dufour et al. (2008). The optical spectra show neutral carbon lines and, in cooler objects, strong molecular carbon bands. The SDSS spectrum of LP 93-21 shows strong C2 Swan bands and C1 lines at λ_{vac} = 4933.40, 5381.83 A together with prominent multiplets at 4770.70, 7116.44 and 7117.17 A. Additional strong lines detected in the SDSS spectra of other warm DQ WDs include C1, λ_{vac} = 4270.22 and 8337.44 A and the multiplet at 9089.34 A.

Radial velocity measurements in warm DQ WDs show large shifts between carbon band heads and atomic lines and between groups of atomic lines due to the Stark effect. Earlier applications of Stark shifts to heavy element line spectra include the analysis of the DAZ WD GALEX J1931+0117 (Vennes, Kawka & Németh 2011). The evidence for Stark shifts in the C1 lines is exposed in the following comparison between laboratory and stellar measurements. We found that in warm DQ WDs carbon lines with highly excited upper levels, i.e., with an ionization energy E_{ion} < 1.2 eV, are systematically red shifted by ≈100 km s^{-1} relative to lines with lower-lying upper levels, i.e., E_{ion} > 1.2 eV. In the high electronic density (n_e ≈ 10^{17} cm^{-3}) environment of these DQ WDs the carbon lines are shaped by the Stark effect. Shock tube experiments (Miller & Bengtson 1970) revealed red shifts of 0.3, 2.2 and 3.0 (n_e/10^{17}) km s^{-1} for three lines of interest at λ_{vac} = 5381.83, 5053.56 and 4934.40 A. These measurements were corroborated and supplemented by Mijatović, Konjević, Kobilarov & Djurović (1995a,b) and a critical review of C1 Stark shifts was presented by Konjević, Lesage, Fuhr & Wiese (2002). Applied to the sample of nine objects, the observed velocity shift between the C1 lines at λ_{vac} = 4933.40 and 5381.33 A is Δv = 106 km s^{-1} and corresponds to an average electronic density in the line forming region of 0.7 × 10^{17} cm^{-3}. Our model atmosphere calculations show that optical depth unity in the atmosphere of these objects, and of LP 93-21 in particular, is achieved in an environment with a neutral helium density of n(He) = 3 – 4 × 10^{20} cm^{-3} and an electronic density n_e = 0.6 – 1.3 × 10^{17} cm^{-3} in overall agreement with densities extracted from the measured average Stark shift.

We used the SDSS spectrum of LP 93-21 to measure the WD’s radial velocity. Following the procedure described above, we first measured the relative shift between C1, λ_{vac} = 5381.83 and 4934.40 A, Δv = 118 km s^{-1}, from which we derived an electronic density n_e = 0.84 × 10^{17} cm^{-3} and, therefore, a Stark shift d(λ_{vac}) = 15.6 km s^{-1}. Subtracting the Stark shift from the raw velocity of 134 ± 13 km s^{-1}, we obtain an apparent velocity γ = 118 ± 16 km s^{-1}. Finally, subtracting a gravitational red shift γ_g = 103 ± 14 km s^{-1}, obtained by averaging mass estimates from Leggett et al. (2018), Kilic et al. (2019) and the present work, we find the corrected radial velocity γ_r = γ – γ_g = 5 ± 21. Interestingly, the observed shift in the C2 bands corrected for the gravitational red shift is γ_r = −11 ± 21 km s^{-1} revealing a small pressure shift toward the blue d(C2) = −26 km s^{-1}.

In summary, we find that LP 93-21 has a large tangential velocity v_{tan} = 4.74 km s^{-1} but a much smaller radial velocity v_r = 17 km s^{-1} than assumed by Ruffini & Casey (2019). Unfortunately, the ratio for their assumed velocity (472 ± 20 km s^{-1}) is obscure since neither cited sources explicitly provide radial velocity measurements and their methodology is unspecified. We can safely assume that neither pressure shift nor gravitational redshift were taken into account by Ruffini & Casey (2019).

The radial velocities for the other members of the sample and for members of the population of hot DQ WDs were calculated in a similar fashion (Kawka et al. 2019, in preparation).

### 2.3 Kinematics

We converted radial velocity and proper motion measurements into the Galactic velocity components using Johnson & Soderblom (1987). We assumed that the solar motion relative

| Parameters | Measurement | Reference |
|------------|-------------|-----------|
| RA (J2000) | 10 45 59.42 | 1         |
| Dec (J2000) | 59 04 51.32 | 1         |
| μ_α cos δ ("y^{-1}) | −1.0192 ± 0.0001 | 1 |
| μ_δ ("y^{-1}) | −1.4625 ± 0.0002 | 1 |
| π (mas) | 17.482 ± 0.135 | 1 |
| G | 17.677 ± 0.002 | 1 |
| G_Rg | 17.683 ± 0.010 | 1 |
| G_g | 17.448 ± 0.016 | 1 |
| u | 17.784 ± 0.011 | 2 |
| g | 17.763 ± 0.005 | 2 |
| r | 17.691 ± 0.006 | 2 |
| i | 17.725 ± 0.007 | 2 |
| z | 17.884 ± 0.018 | 2 |

References: (1) Gaia Collaboration, et al. (2018); (2) Aguado et al. (2019)
to the local standard of rest is \((U, V, W) = (11.1, 12.2, 7.3) \text{ km s}^{-1}\) (Schönrich et al. 2010). The resulting velocity vector \((U, V, W) = (-201, -420, 57) \text{ km s}^{-1}\) (Table 2) immediately suggests that LP 93-21 is bound to the Milky Way but also that it does not belong to the Galactic disc but, instead, to the Galactic halo. Sion et al. (1988) investigated the kinematical properties of various subgroups of the WD population and noted that DQ WDs have higher than average space velocities and a higher fraction of halo candidates than the other WD subgroups.

Using the velocity components \((U, V, W)\), we calculated the Galactic orbit and kinematic properties using the Numerical Integrator of Galactic Orbits (NIGO) developed by Rossi (2015) and the Galactic potential described as model A in Contigiani, Rossi & Marchetti (2019). In this model the total mass of the Milky Way is \(9 \times 10^{11} M_\odot\). Fig. 1 shows the calculated \(z\)-component of the angular momentum, \(L_z\), against the orbital eccentricity, \(e\), for a sample of 36 hot and warm DQ WDs including LP 93-21.

### 3 DISCUSSION

Based on the stellar and kinematical properties of LP 93-21, we now determine its population membership and likely progenitors.

#### 3.1 Population Membership

Pauli et al. (2003) presented a method to clearly distinguish halo WDs from WDs belonging to the thin and thick discs using \(L_z\) and \(e\). Fig. 1 shows that a few objects in the warm/hot DQ population belong to the thick disc and that LP 93-21 exhibits unique halo properties with a retrograde orbit. Pauli et al. (2006) showed that 2 per cent of WDs belong to the Galactic halo including a few objects with retrograde orbits like that of LP 93-21.

Fig. 2 shows the calculated orbit of LP 93-21 in the meridional \(R-z\) plane and Table 3 summarizes its orbital properties. The orbit appears to have some of the attributes of an inner-halo object although its highly retrograde motion points to a different origin for LP 93-21. The results of Matsuno et al. (2019) are important for this work because they allow us to understand to which population LP 93-21 may belong. Matsuno et al. (2019) divide the \(E-L_z\) plane in four regions, namely, (A) the innermost halo, whose objects are characterized by small energies \(E\) and a prograde motion, (B) the Gaia Enceladus (Helmi et al. 2018), with high \(E\) and low \(L - z\) objects, (C) the high \(E\) retrograde motion stars and (D) the high \(E\) and prograde motion stars (only selected to conduct comparison studies to region (C) and thus of no interest in the present context). The energy of LP 93-21 \((E = -1.4 \times 10^{5} \text{ km s}^{-2})\) and its retrograde orbit \((L_z = -1491 \text{ kpc km s}^{-1})\) place it in the vicinity of Matsuno et al. (2019) subgroup (C). Adopting their dispersion values for \((E, L_z)\) we find that LP 91-23 lies within \(\approx 2.7\sigma\) of the average \((E, L_z)\), i.e., where 7 out of 1000 members should reside. Matsuno et al. (2019) find that population (C) has the lowest metallicity indicating that the genesis of this retrograde population is neither linked to the innermost halo nor to the Gaia Enceladus population. Furthermore, the very low alpha element abundances of population (C), suggestive of inefficient star formation, indicates that this retrograde population originally belonged to a satellite dwarf galaxy of the Milky Way that was much smaller than the satellite galaxy that produced the Gaia Enceladus. Additionally, the EAGLE simulations of galaxy formation conducted by Mackereth et al. (2019) have shown that stars originating from the earliest accretion events have a median \(e\) of about 0.5 (LP 93-21 has \(e = 0.6\)), whilst the median \(e\) of the most recently (i.e., at redshifts \(z < 1.5\)) accreted satellites is around 0.8 (but up to \(> 0.9\)). Alternatively, LP 93-21 could have formed in the Milky Way but, following a merger with a satellite galaxy, its motion migrated to a retrograde halo orbit (Bonaca et al. 2017). Using simulations, Bonaca et al. (2017) showed that more than 95 per cent of halo stars would have formed before the last significant merger that occurred about 7 Gyr ago. These observational and theoretical results impose a total age larger than 7 Gyr for LP 93-21.

#### 3.2 The progenitor stars of LP 93-21

The progenitor of the DQ WD LP 93-21 cannot be a single main sequence star because its \(1.1 M_\odot\) mass implies a progenitor of about \(6 M_\odot\) (e.g., Ferrario et al. 2005) that would evolve to the WD stage in \(\leq 100\) Myr. Therefore, under the single star evolution scenario, the total age of LP 93-21 could not be significantly larger than its \(\sim 2.3\) Gyr cooling age. Furthermore, such a relatively massive star would have been born in the spiral arms of the Galaxy where star formation is thriving. As a consequence, the motion of LP 93-21 should be well and truly confined to the thin disk. The only possible explanation of this age paradox is that LP 93-21 is the end product of...
binary evolution that terminated with the merging of its two stellar components. The likely progenitor system of LP 93-21 probably consisted of two Carbon Oxygen (CO) WDs that formed many billion years ago and then slowly approached each other under the influence of gravitational radiation to finally merge 2.3 Gyr ago. We favour this double degenerate merging route because it can easily explain both the large mass of LP 93-21 and its carbon enriched atmosphere. Although the stellar merging hypothesis can solve the single progenitor puzzle, it still cannot explain the highly retrograde motion of LP 93-21. There are two possible explanations of this second puzzle; either the progenitor stars of LP 93-21 belonged to a satellite galaxy that was accreted by the Milky Way in ancient times or LP 93-21 was born in situ but was later driven onto a highly retrograde halo orbit due to the accretion, that occurred more than 7 Gyr ago, of a satellite galaxy (see section 2.3). Both hypotheses require the age of LP 93-21 to be at least three times larger than implied from single star evolution.

In order to understand the genesis of LP 93-21 we have employed the rapid binary star evolution algorithm, {	extsc{wser}}, of 	extcite{Hurley, Tout & Pols 2002} and evolved binaries from the main sequence to an age of 11 Gyr. This age, added to the 2.3 Gyr cooling age, is still below the age of the Galaxy and of its ancient satellites.

When stars evolve off the main sequence, their envelopes expand significantly. If a companion star is present and is on a sufficiently close orbit, the newly formed giant fills its Roche lobe and starts transferring mass to its companion, but at a rate that is far too high for the companion to accept. This results into an ever expanding giant whose outer layers engulf both stars till their envelopes merge into one another. This phase of evolution has been named “common envelope” (see 	extcite{Izzard et al. 2012}). The {	extsc{wser}} code uses the $\alpha_{\text{CE}}$ formalism, where $\alpha_{\text{CE}}$ is the common envelope efficiency parameter (Hurley, Tout & Pols 2002). In the present calculations we have adopted $\alpha_{\text{CE}} = 0.2$, which is consistent with the values used by Briggs et al. (2015) and Briggs et al. (2018) to model the characteristics of magnetic WDs under the assumption that they originate either via common envelope merging events or double degenerate mergers (see also 	extcite{Wickramasinghe, Tout, & Ferrario 2014}).

Stellar merging events are common in the Galaxy, as highlighted by the large shortfall of WD binaries in the solar neighbour- hood, as first noted by 	extcite{Ferrario 2012} and later modelled by 	extcite{Toonen et al. 2017} in terms of binaries lost to merging events during the course of their evolution. It is unlikely that the incidence of binary was lower in ancient environments. On the contrary, the detailed studies of 	extcite{Machida et al. 2009} have revealed that given the same median rotation parameter as in the solar neighbourhood, if a gas cloud has a metallicity $< 10^{-4}$ most stars are born as members of binary/multiple systems.

Our synthetic population was generated using a Monte Carlo approach. The masses $M_1 (\leq 1 - 8 M_\odot)$ of the main sequence primaries were drawn from a Salpeter’s initial mass function (Salpeter 1955) whilst the masses $M_2 (0.8 - 8 M_\odot)$ of the companions were drawn from a uniform mass distribution (e.g. Ferrario 2012). The initial orbital periods $P_0$ were drawn from a logarithmically uniform distribution ($2 < \log_{10}(P_0/d) < 4$). The evolved population was then searched for systems that produced double WDs that merged after a total life-span of around 7 to 11 Gyr to yield a single massive WD like LP 93-21. We have found that a typical binary that could be a suitable progenitor of LP 93-21 was initially composed of two stars with masses of 2.1 M$_\odot$ and 1.8 M$_\odot$ and an initial period of 1184 days. After about 1 Gyr, the primary star evolves off the main sequence, becomes a red giant, ignites helium in its core and then evolves to become a super-giant star that loses about 0.3 M$_\odot$ in stellar winds. During the AGB evolution the stellar envelope expands and forms a common envelope with its companion. This brings the two stars closer together due to friction within the common envelope. The envelope is then ejected exposing the newly formed CO WD. Now the two stars are on a much tighter orbit. The primary is a CO WD with a mass of 0.58 M$_\odot$, while the secondary, largely unaffected by the events unfolded so far, is still on the main sequence. About 184 Myr later, the secondary star becomes a red giant, ignites helium in its core and then starts its ascent along the AGB. It is during the AGB evolution that the secondary star initiates a second common envelope at the end of which it will emerge as CO WD with a mass of 0.53 M$_\odot$. The orbital period is now only 0.344 days. It has taken the two stars about 1.696 Myr to become a double degenerate system. From this point onward the orbit slowly shrinks due to gravitational radiation until, after 9.4 Gyr, the two CO WDs coalesce to produce a 1.1 M$_\odot$ WD. After cooling for about 2.3 Gyr this massive WD with a carbon enriched atmosphere will reach $T_{\text{eff}} \sim 10,000$ K and a total age of 13.3 Gyr. Although this is probably at the upper end of its possible age, a different combination of initial masses and orbital periods can yield younger objects.

Gaia photometry and parallax measurements have revealed a pile-up of high-mass WDs (Gaia Collaboration, et al. 2018a) on the Hertzsprung–Russell diagram which has been labelled the Q branch. This has been interpreted by Tremblay et al. (2019) as evidence of WD’s crystallization whose onset delays cooling and causes this pile-up. However, Cheng et al. (2019) have shown that the Q branch stars, of which half are DQs, have significantly older kinematics and therefore require an additional cooling delay of 8 Gyr to explain the pile-up which is most likely caused by the settling of $^{22}$Ne. Because this settling which affects only about 6% of high mass white dwarfs, favours CO cores and massive CO WDs cannot evolve from single star evolution, Cheng et al. (2019) concluded that those WDs that experience this cooling delay must be the products of WD mergers. According to this scenario, since LP 93-21 is cooler than the WDs on the Q branch, it would have undergone this additional cooling.

\begin{table}[h]
\centering
\caption{Properties of LP 93-21.}
\begin{tabular}{lll}
\hline
Parameter & Measurement & Reference \hline
$T_{\text{eff}}$ (K) & 9730±49, 8690±120, 9360±200 & 1,2,3 \\
log $g$ (cgs) & 8.90±0.02, 8.70±0.02, 8.84±0.02 & 1,2,3 \\
log C/He & −2.73, −3.51, −3.12 ± 0.13 & 1,2,3 \\
Mass ($M_\odot$) & 1.139±0.011, 1.029±0.015, 1.10±0.01 & 1,2,3 \\
Cooling Age (Gyr) & 2.366±0.020, 2.71±0.08, 2.28±0.10 & 1,2,3 \\
Distance (pc) & 57.2 ± 0.4 & 4 \\
$\gamma_g$ (km s$^{-1}$) & 102.5±14.2 & 3 \\
$v_t$ (km s$^{-1}$) & 15 ± 21 & 3 \\
$U$, $V$, $W$ (km s$^{-1}$) & −201 ± 11, −420 ± 7, 57 ± 16 & 3 \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\centering
\caption{Galactic orbits}
\begin{tabular}{lll}
\hline
Parameters & Measurement & Notes \hline
$e$ & 0.573$^{+0.058}_{-0.053}$ & averaged \\
$R_{\text{max}}$ (kpc) & 14.53$^{+1.12}_{-0.43}$ & averaged \\
$Z_{\text{max}}$ (kpc) & 2.0 & extremum \\
$L_c$ (kpc km s$^{-1}$) & −1491$^{+59}_{-58}$ & \\
$E$ (km² s$^{-2}$) & −1.40 ± 0.03 $\times 10^7$ & \\
\hline
\end{tabular}
\end{table}

References: (1) Leggett et al. (2018); (2) Kilic et al. (2019); (3) This work; (4) Gaia Collaboration, et al. (2018).
4 CONCLUSIONS

We found that the DQ WD LP 93-21 is bound to the Milky Way and that its orbit is quite energetic and highly retrograde. Our kinematic study is based on a careful examination of its carbon line spectrum and a proper evaluation of its radial velocity. The kinematics of LP 93-21 resembles that of a stellar population associated to the ancient merger of a dwarf galaxy with the Milky Way. The kinematics of LP 93-21 and the inferred antiquity are incompatible with single star evolution which would impose a total age < 3 Gyr. We conclude that this star emerged out of the evolution of two CO WDs resulting in a total age >10 Gyr. Our results exclude earlier suggestions (Ruffini & Casey 2019) that LP 93-21 belongs to a class of surviving remnants of subluminous Type Iax supernova events (Vennes et al. 2017; Raddi et al. 2019).

The stellar properties of LP 93-21 do not distinguish it from any other members of the warm/hot DQ population. Its high mass and large carbon abundance are entirely consistent with population average. As the prototype of an old WD population, our study of LP 93-21 suggests that as a whole, warm DQ WDs are the product of stellar mergers, most likely double degenerate mergers.

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and thus its total cooling age should be ~ 10 Gyr rather than ~ 2.3 Gyr. If this is correct the stars forming the progenitor binary of LP 93-21 must have been more massive and evolved to the ultimate merger event in less than a few Gyrs to yield a total age that is less than the age of the Galaxy and its ancient satellites.

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