A hyper-runaway white dwarf in Gaia DR2 as a Type Iax supernova primary remnant candidate

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ABSTRACT

Observations of stellar remnants linked to Type Ia and Type Iax supernovae are necessary to fully understand their progenitors. Multiple progenitor scenarios predict a population of kicked donor remnants and partially burnt primary remnants, both moving with relatively high velocity. But only a handful of examples consistent with these two predicted populations have been observed. Here we report the likely first known example of an unbound white dwarf that is consistent with being the fully cooled primary remnant to a Type Iax supernova. The candidate, LP 93-21, is travelling with a galactocentric velocity of \( v_{\text{gal}} \approx 605 \, \text{km s}^{-1} \), and is gravitationally unbound to the Milky Way. We rule out an extragalactic origin. The Type Iax supernova ejection scenario is consistent with its peculiar unbound trajectory, given anomalous elemental abundances are detected in its photosphere via spectroscopic follow-up. This discovery reflects recent models that suggest stellar ejections likely occur often. Unfortunately the intrinsic faintness of white dwarfs, and the uncertainty associated with their direct progenitor systems, makes it difficult to detect and confirm such donors.

Key words: supernovae: Type Ia, Type Iax – white dwarfs – stars: individual: LP 93-21 – stars: kinematics and dynamics.

1 INTRODUCTION

Type Ia supernovae (SNe Ia) are the thermonuclear explosions of carbon–oxygen (C/O) white dwarfs (WDs; Nomoto 1982; Iben & Tutukov 1984). SNe Ia have been used to calibrate cosmological distance scales (Nomoto, Iwamoto & Kishimoto 1997; Perlmutter et al. 1999) and cosmological models (Riess et al. 1998), yet our knowledge on the progenitors of SNe Ia remains incomplete. Although the precise progenitor system is unknown, it is generally accepted a primary WD is stimulated via mass accretion from, or merges with, a companion to explode as an SN Ia (Wang & Han 2012).

In the so-called ‘single-degenerate’ (SD) scenario (Whelan & Iben 1973; Nomoto 1982), the companion is a non-degenerate hydrogen- or helium-star (H-star and He-star, respectively) which donates material from its outer layers to the primary, mass-accreting WD. In the ‘double-degenerate’ (DD) scenario (Iben & Tutukov 1984; Webbink 1984), the donating companion is another WD. A merger is possible in either scenario. Whether or not a primary WD and companion star will lead to the SD or DD scenario depends on parameters such as the initial masses of the components, their separation, and metallicity (Iben & Tutukov 1994; Wang & Han 2010). These parameters also determine which of the many sub-channels each scenario will likely take (Wang & Han 2011; Liu, Wang & Han 2018).

The explosion of the primary WD can be triggered multiple ways in either scenario (Iben & Tutukov 1984; Webbink 1984; Pakmor et al. 2012; Seitenzahl et al. 2013; Papanj et al. 2015; Shen et al. 2018b). Theory and observations both suggest different combinations of triggering mechanisms may describe various observed abundance patterns in SN Ia remnants (Seitenzahl et al. 2013; Fink et al. 2014). This implies that both near-Chandrasekhar (near-Ch) mass WDs and sub-Chandrasekhar (sub-Ch) mass WDs, either in the SD or DD scenario, explode to contribute to all observed SNe Ia.

Recent models suggest that the donor will almost always survive the explosion (Pan, Ricker & Taam 2012a; Liu et al. 2018; Shen et al. 2018a). In cases of complete primary WD detonation, the surviving companion will be kicked away with a velocity roughly equal to the binary’s pre-explosion orbital velocity (Eldridge, Langer & Tout 2011; Wang & Han 2011). This population of kicked non-degenerate/degenerate stars should show evidence of the SN Ia in their photosphere (Pan et al. 2012a; Pan, Ricker & Taam 2012c; Shen & Schwab 2017; Shen et al. 2018a; Tanikawa, Nomoto & Nakasato 2018). Regardless of the evolutionary stage of the kicked donor, it will ultimately evolve to the main WD cooling sequence (Hansen 2003; Justham et al. 2009). Therefore a population of kicked WDs are expected from the SN Ia scenario, harbouring...
evidence of their close proximity to thermonuclear supernova. We denote this entire kicked WD population as donor remnants (DRs) regardless of their evolutionary phase during the progenitor stage.

It has also been suggested that the primary WD can survive its own failed detonation in a subluminous SN Iax event (Foley et al. 2013; Kromer et al. 2013). If the primary WD remains intact, the asymmetry in the partial deflagration could lead to its ejection from the binary and tell-tale ashes may remain visible in its photosphere (Jordan et al. 2012). It has also been argued that the partial deflagration does not warrant an ejection of the companion (Kromer et al. 2013; Fink et al. 2014). In either case, the possibly intact primary WD is a different kind of remnant – one that should show evidence of the subluminous SN Iax in their own photosphere. These ‘primary remnants’ (PRs) should also eventually fall to the Galactic Centre in the mid-plane (Miyamoto & Nagai 1975), and a spherical NFW dark matter halo potential (Navarro, Frenk & White 1996). The relative weighting for each component is taken from Bovy (2015; see their Figure 1).

LP 93-21\(^1\) is a single, DQ spectral-type WD, known since 1976 to have strong carbon Swan Bands and a peculiarly high proper motion (Luyten 1976). In this paper, we examine the properties of LP 93-21 and argue that it is an evolved PR which was kicked to its abnormally high space velocity by its own partial deflagration. We also discuss the possibility that LP 93-21 may also be an evolved donor. In Section 2, we present recent observational data and atmospheric analysis of LP 93-21 to provide updated estimates of its total space motion, mass, age, and origin. In Section 3, we analyse the kinematics of LP 93-21 in context with these updated estimates and assess the viability of the SNe Ia/Iax progenitor scenario. We conclude in Section 4.

2 OBSERVATIONS

Here we report on the most up-to-date observations and parameter estimates of LP 93-21. LP 93-21 was first examined in detail by Greenstein et al. (1977) as a carbon degenerate. Its spectrum showed particularly strong C\(_2\) molecular bands, and its proper motion made it a high-velocity WD. The Sloan Digital Sky Survey (SDSS) has spectroscopic confirmation of over 19 000 white dwarfs, most with reported radial velocities (Kleinman et al. 2013; Blanton et al. 2017; Abolfathi et al. 2018). The European Space Agency’s Gaia satellite has also observed over 25 000 white dwarfs, measuring their proper motion and parallax with milliarcsecond accuracy (Gaia Collaboration 2016; Gaia Collaboration 2018; Lindegren et al. 2018). Both surveys have since re-observed LP 93-21, providing improved measurements which confirm both its peculiarly fast motion and strong carbon spectral features.

2.1 Kinematics

The high precision of Gaia DR2 measurements (see Table 1) for LP 93-21 provide a parallax measurement of \(\pi = 17.48 \pm 0.14\) mas that can be directly converted to distance \(d = 57.2^{+0.4}_{-0.1}\) pc without significant loss of accuracy (Bailer-Jones et al. 2018; Luri et al. 2018). We may calculate the 3D space motion for LP 93-21 by combining Gaia’s proper motion measurements and the SDSS radial velocity measurement. We include the radial velocity measurement from its SDSS spectrum of 462 km s\(^{-1}\) (Kleinman et al. 2013) and add a conservative radial velocity error of \(\pm 20\) km s\(^{-1}\), which we assume is uncorrelated with the Gaia observables.

To integrate LP 93-21’s orbit, we used the ASTROPY (Astropy Collaboration 2013, 2018) affiliated PYTHON package GALA\(^2\) (Price-Whelan 2017). We chose the Milky Way potential in GALA which assumes a mass model containing a spherical nucleus and bulge based on the Hernquist potential for a spheroid (Hernquist 1990), a disc based on the Miyamoto–Nagai potential for a flattened mass distribution (Miyamoto & Nagai 1975), and a spherical NFW dark matter halo potential (Navarro, Frenk & White 1996). The relative weighting for each component is taken from Bovy (2015; see their Table 1). We define the Sun’s position at \(x = -8.3\) kpc from the Galactic Centre in the mid-plane (\(z = 0\)) of the Milky Way, and use an upper-limit circular velocity estimate of 250 km s\(^{-1}\) (Bovy et al. 2012; Eilers et al. 2019). We drew initial positions for each orbit from the observed covariance matrix, as described in Lindegren et al. (2018), which factors in the correlation between the Gaia observables.

We find LP 93-21 is currently travelling at approximately \(v_{\text{gal}} = 605\) km s\(^{-1}\) with a local galactic escape speed of approximately \(v_{\text{esc}} = 557\) km s\(^{-1}\), making it locally unbound to the Milky Way’s gravitational potential. At a distance of \(d = 57.2^{+0.4}_{-0.1}\) pc, LP 93-21

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Table 1. Measured properties of LP 93-21.

| Parameter                        | Symbol | Value   | Units     | Source                  |
|----------------------------------|--------|---------|-----------|-------------------------|
| Right ascension                  | \(\alpha\) | 161.49 ± 0.08 | deg       | Gaia Collaboration (2018) |
| Declination                      | \(\delta\) | 59.07 ± 0.10 | deg       | Gaia Collaboration (2018) |
| Proper motion in right ascension | \(\mu_{\alpha}\) | −1019.19 ± 0.14 | mas yr\(^{-1}\) | Gaia Collaboration (2018) |
| Proper motion in declination     | \(\mu_{\delta}\) | −1462.53 ± 0.17 | mas yr\(^{-1}\) | Gaia Collaboration (2018) |
| Parallax                         | \(\pi\) | 17.48 ± 0.14 | mas        | Gaia Collaboration (2018) |
| Radial velocity                  | \(v_{\text{rad}}\) | 462 ± 20 | km s\(^{-1}\) | Abolfathi et al. (2018) |
| Apparent G-band magnitude        | \(G_{\text{app}}\) | 17.7 | mag | Gaia Collaboration (2018) |
| Absolute G-band magnitude        | \(G_{\text{abs}}\) | 13.8 | mag | Gaia Collaboration (2018) |
| BP – RP colour                   | \(C_{\text{BP-RP}}\) | 0.24 | mag | Gaia Collaboration (2018) |
| Mass                             | \(M\) | 1.029 ± 0.015 | M\(_{\odot}\) | Kilic et al. (2018) |
| Effective temperature            | \(T_{\text{eff}}\) | 8690 ± 120 | K | Kilic et al. (2018) |
| Surface gravity                  | \(\log g\) | 8.701 ± 0.02 | cm s\(^{-2}\) | Kilic et al. (2018) |
| Carbon abundance                 | [C/He] | −3.51 | dex | Kilic et al. (2018) |
| White dwarf cooling age           | \(t_{\text{WD}}\) | 2.715 ± 0.08 | Gyr | Kilic et al. (2018) |

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\(^1\) Also known as LHS 291 (Luyten 1976), EGGR 434 (Greenstein et al. 1977), WD 1042+593 and WD 1042 + 59 (McCook & Sion 1999), and SDSS J104559.13+590448.3, SDSS J104559.14+590448.3, and SDSS J104559.15 + 590448.2 (Abolfathi et al. 2018).

\(^2\) https://gala-astro.readthedocs.io/en/latest/index.html
is the closest hyper-runaway star to the Sun. Fig. 1 shows LP 93-21’s integrated orbit forwards and backwards in time 250 Myr – approximately the time-scale of one Solar orbit around the Galactic Centre. For all 100 orbits drawn, LP 93-21 is unbound to the Milky Way’s gravitational potential. Fig. 2 shows its proximity to the Sun. LP 93-21’s closest approach to the Sun would have been approximately 70,000 yr ago at a distance of about 46 pc.

The observed velocity of LP 93-21 is currently being influenced by the Milky Way’s gravitational potential. By integrating LP 93-21’s orbit in GALA, we take into account its velocity over time only as it has been affected by the Milky Way’s gravitational potential. If we consider an extragalactic origin for LP 93-21 then as it approached the disc of the Milky Way the gravitational pull began to accelerate it and increase its speed (see Fig. 3, bottom right).

If LP 93-21 did have an extragalactic origin, then by integrating backwards we find that at a distance of approximately 100 kpc from the Galactic Centre (taken as a proxy for the virial radius of the Milky Way), LP 93-21’s galactocentric velocity is about 400 km s$^{-1}$. This would correspond to a flight time of about 220 Myr from a 100 kpc galactocentric radius to LP 93-21’s current position. This provides an upper limit for ejection time if the SN kick occurred within the Milky Way.

Based on kinematic information alone, we can exclude the Galactic Centre as the origin of LP 93-21, as well as the Magellanic clouds, and six known supernova remnants (SN1006A, SN1054A, SN1604A, SN185A, SN393A, and Vela; Green 2014). Fig. 3 shows the kinematic and positional evolution for LP 93-21. The galactocentric z-coordinate $z_{\text{gal}}$, galactocentric radius $R_{\text{gal}}$, and heliocentric distance $d_{\text{helio}}$ all show asymptotic behaviour, characteristic of unbound stars.

2.2 Current mass and age estimates

Kilic et al. (2018) identified 142 Gaia sources as halo WDs and presented detailed model atmosphere analysis for each one based on Gaia parallaxes and optical and near-infrared photometry. They used a pure helium atmosphere model with trace amounts of carbon to simultaneously fit the spectral energy distribution (SED) and the optical spectra for LP 93-21. The results of this fit are summarized in Table 1. Weidemann (2005) notes the inaccuracies of using He-dominated DB WD models as a replacement for DQ WDs without accounting for this enhanced carbon composition, implying that the detailed analysis by Kilic et al. (2018) is the current state-of-the-art. LP 93-21’s mass is found to be 1.03 M$_\odot$, making it a massive outlier in SDSS (Kepler et al. 2007; see their Fig. 13). LP 93-21’s WD age is estimated by Kilic et al. (2018) to be 2.715 Gyr, under the assumption of zero mass transfer.

Leggett et al. (2018) presented new US Naval Observatory Flagstaff Station parallaxes for over 170 WDs. They combined recent Gaia parallaxes with photometry spanning from the mid-infrared to the ultraviolet to determine flux-calibrated SEDs for each WD. The SEDs were compared to flux distributions provided by various recent model atmospheres compiled by the authors. Leggett et al. (2018) demonstrate the models reproduce the full SED very well for the entire sample of WDs. LP 93-21’s mass is again found to be an outlier at 1.14 M$_\odot$, and its WD age is estimated to be 2.366 Gyr, under the assumption of zero mass transfer.

3 DISCUSSION

LP 93-21 is an exceptionally fast-moving WD, moving much quicker than would be expected for a normal, Milky Way halo WD (Oppenheimer et al. 2001; Bergeron 2003; Bergeron et al. 2005; Pauli et al. 2006; Ducourant et al. 2007). LP 93-21’s observed velocity likely excludes it from normal dynamical ejection from a globular cluster because simulations estimate that ≈99 per cent of all dynamical ejections of this type have less than 200 km s$^{-1}$ velocities (Perets & Subr 2012). LP 93-21’s observed velocity also likely excludes it from the core-collapse binary supernova ejection scenario. Simulations estimate that only the fastest few per cent of stars ejected via core-collapse supernovae reach speeds of over 200 km s$^{-1}$ (Tauris 2015).

If LP 93-21 originates from the Milky Way, we find its velocity was very likely never below 400 km s$^{-1}$. Therefore, the mechanisms that may explain LP 93-21’s velocity (if from the Milky Way) include dynamical ejection from the Galactic Centre or a binary SNe Ia/Iax ejection. Given LP 93-21 does not originate from the Galactic Centre (or any other location where a central, massive black hole is expected to be, see Fig. 1), and can be excluded from other dynamical scenarios based on its observed speed, the most plausible mechanism to describe its velocity is the SNe Ia/Iax ejection scenario.

The progenitor configuration most compatible with LP 93-21’s observed speed is the SD scenario proposed for SNe Ia/Iax between a primary WD and He-burning donor star (Wang & Han 2009; Wang, Poodsiadowski & Han 2017; Bauer, White & Bildsten 2019; Wong & Schwab 2019). In the SN Ia scenario, the primary WD reaches Chandrasekhar-mass through accretion, explodes as an SN Ia, and the DR is ejected at roughly the pre-SN orbital velocity (Eldridge et al. 2011; Tauris 2015; Shen et al. 2018a). In the SN Iax scenario, ejection speeds on the order of a few tens to a few hundred km s$^{-1}$ are expected for both the DR and PR, due to the expected asymmetric explosion and ejecta interaction (Jordan et al. 2012; Liu et al. 2012, 2013b; Pan, Ricker & Taam 2012b, d; Kromer et al. 2015).

It is unlikely that LP 93-21 was a WD while donating mass to its former primary companion in the DD scenario. Due to the relatively short upper-limit Milky Way flight time of 220 Myr for LP 93-21 (see Section 2.1), its maximum Milky Way speed was likely never above ≈ 625 km s$^{-1}$ (see Fig. 3). The expected tell-tale kinematic signature (i.e. $> 1000$ km s$^{-1}$ in all cases) indicates LP93-21 should still be possessing a much quicker total speed if it were ejected as a WD in the DD scenario (Shen et al. 2018a; Tanikawa et al. 2018). This is also indicated by Fig. 1. If shot through the Milky Way’s disc with a characteristic speed of $> 1000$ km s$^{-1}$, LP 93-21 should have only been accelerated to quicker speeds after its ejection. Thus, the DD scenario is unlikely for LP 93-21 based on its observed speed alone.

The SD SN Ia scenario implies LP 93-21 was a mass-donating He-star companion that was ejected by the detonation of its primary. In this scenario the relatively short upper-limit Milky Way flight time of 220 Myr for LP 93-21 (see Section 2.1), when combined with the updated WD cooling age estimates of over 2 Gyr from both Kilic et al. (2018) and Leggett et al. (2018), demands an origin from elsewhere than the Milky Way. LP 93-21 would have then evolved into a WD while travelling through intergalactic space. We find this scenario is an unlikely explanation for LP 93-21’s origin because of the low probability that an extragalactic hyper-runaway star would pass so close to the Sun. We took over 850 nearby galaxies from the Updated Nearby Galaxy Catalog

3\footnote{In the same way, the SN Iax scenario also implies LP 93-21 may have been a former He-star donor.}
Hyper-runaway white dwarf in Gaia DR2

Figure 1. LP 93-21’s orbit. The current position of LP 93-21 is shown by a black circle. The integrated orbits trace LP 93-21’s movement forward in time (red) and backwards in time (blue). The spread in orbit directions is caused by the uncertainty in Gaia and SDSS measurements. The extent of the Milky Way’s spiral arms are approximated by the darker, dashed circle, and the Galactic Centre is approximated by the intersection of the lighter, dashed lines. The direction to the Large Magellanic Cloud is denoted by a black arrow. Each hash mark indicates approximately 25 million years of flight either forwards or backwards in time. Note LP 93-21 is unbound in all 100 integrated orbits.

Figure 2. LP 93-21’s proximity to the Sun. The current position of LP 93-21 is shown by a black circle. The position of the Sun is denoted by a yellow star. The integrated orbits trace LP 93-21’s movement forward in time (red) and backwards in time (blue). The spread in orbit directions is caused by the uncertainty in Gaia and SDSS measurements. LP 93-21’s closest approach around 70,000 yr ago was approximately 46 pc.

(Karachentsev, Makarov & Kaisina 2013) and estimated SN Ia rates given the galaxy mass and rate-size relations from Li et al. (2011). We assume an average speed of 600 km s\(^{-1}\), which assumes some deceleration as the DR escapes the gravitational potential of the host galaxy and acceleration as the DR approaches the Milky Way. If we assume that the DRs are ejected in isotropic directions and that a fully cooled down DR could be observed by Gaia out to a distance of 100 pc, then the expected number of observable DRs from a the nth galaxy is given by the ratio of observable volume to the volume of a sphere with a radius equal to the galaxy’s distance

\[
E_n = \left( \frac{100 \text{ pc}}{d_n} \right)^3 \text{SNuM}(M_n) \Delta t
\]  

where \(d_n\) is the distance to the host galaxy, and \(\text{SNuM}(M_n)\) is the SN Ia rate as a function of galaxy mass. Here \(\Delta t\) is conservatively taken as the maximum time the DR could take to pass through the observable volume: the time taken for DR to travel twice the observable radius (towards and away from us; \(\Delta t = 2 \frac{100 \text{ pc}}{600 \text{ km s}^{-1}} \approx 3.3 \times 10^6 \text{ yr}\)). After summing the expected number of observable DRs from all nearby galaxies we find that only \(10^{-4}\) of fully cooled, extragalactic DRs would be expected. This value remains much less than one even if we relax our assumptions. This low expectation value indicates it is highly unlikely any extragalactic DR is within 100 pc of the Sun, including LP 93-21.

If ejected as a He-star, a corresponding rotation speed and detailed elemental abundances would be paramount in determining the viability of this scenario for LP 93-21. It is expected that LP 93-21 would be a very fast rotator, and that a non-trivial abundance of decayed nickel might still be visible on its surface (Fuller & Lai 2012; Pan et al. 2012b; Liu et al. 2013a). Trace amounts of intermediate-mass elements might also point to the He-star SD SN Ia channel as the explanation for LP 93-21’s observed speed (Pan et al. 2012d; Liu et al. 2013b).

Conversely, the SN Iax explanation implies LP 93-21 was possibly a former primary WD in the same SD configuration between a WD and companion He-star. The upper-limit Milky Way flight time is now consistent with its WD cooling age, by this explanation. Primary WDs which have possibly survived their own partial deflagrations make a new class of stars based on distinct kinematic and abundance signatures (Raddi et al. 2019). The observed speeds of these objects agree well with LP 93-21’s. But as shown by the red dot in Fig. 4, these objects do not appear as ordinary WDs. The handful of objects found appear to be ‘puffed-up’ WDs, meaning they are brighter and slightly redshifted when compared to ordinary WDs (as expected, and consistent with the observed speeds). This suggests that these are puffed-up WDs, which are brighter and slightly redshifted when compared to ordinary WDs.

\[ E_n = \left( \frac{100 \text{ pc}}{d_n} \right)^3 \text{SNuM}(M_n) \Delta t \]
Figure 3. Kinematic and positional parameters for LP 93-21 shown as a function of flight time $t$. Movement forward in time is denoted in red and movement backwards in time is denoted in blue. Top left: galactocentric $z$-coordinate $Z_{\text{gal}}$. The vertical extent of the thick disc is approximated by the dashed lines. Top right: galactocentric radius $R_{\text{gal}}$. Bottom left: heliocentric distance $d_{\text{helio}}$. Bottom right: galactocentric rest-frame velocity $v_{\text{gal}}$.

LP 93-21's orbit implies that it has travelled at most 220 Myr if originating from the Milky Way. The SN Iax-ejection scenario is consistent with its observed velocity, and a detailed spectrum may confirm if LP 93-21’s own partial deflagration in an SN Iax caused such an ejection from the Milky Way.

If a portion of SNe Ia/Iax progenitors are a result of the He-star donor channel, the post-explosion kinematics necessarily produces a population of single WDs with high velocities, possibly containing distinguishing elemental abundances (Wang & Han 2009; Liu et al. 2018; Wang 2018; Raddi et al. 2019; Zhang et al. 2019). Thus it is possible that many high-velocity, slightly evolved He-stars and high-velocity WD remnants originate from both the SN Ia and SN Iax progenitor channels.

However, WDs are intrinsically very faint, so magnitude-limited surveys have historically had difficulties finding representative populations for WD analysis outside the Solar neighbourhood.

4 CONCLUSIONS

Using Gaia DR2, we were able to confirm LP 93-21 exhibits a total space velocity of approximately $v_{\text{gal}} = 605 \, \text{km s}^{-1}$, with a local galactic escape speed of approximately $v_{\text{esc}} = 557 \, \text{km s}^{-1}$. We found its orbit to be unbound to the Milky Way in all cases. LP 93-21’s orbit implies that it has travelled at most 220 Myr if originating from the Milky Way. The SN Iax-ejection scenario is consistent with its observed velocity, and a detailed spectrum may confirm if LP 93-21’s own partial deflagration in an SN Iax caused such an ejection from the Milky Way.

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However, WDs are intrinsically very faint, so magnitude-limited surveys have historically had difficulties finding representative populations for WD analysis outside the Solar neighbourhood.
LP 93-21’s chance proximity to the Sun enabled discovery and observations easier than most for the likely numerous WD remnants kicked in the SNe Ia/Iax scenarios. In the future, magnitude-limited surveys should improve for very faint magnitudes and many more ‘cooled-down’ remnants of these scenarios are likely to be found.

Regardless of the origin, LP 93-21 is the closest hyper-runaway WD candidate to the Sun. Other SNe Ia/Iax progenitor remnant candidates are shown on a Hertzsprung–Russell diagram of $BP - RP$ colour versus absolute $G$-band magnitude in Fig. 4. In four cases, a detailed spectral analysis was used in conjunction with a kinematic analysis to constrain the nature of the progenitor systems that likely caused their high velocities. All four candidates were WDs found to be enhanced in key elements and unbound to the Milky Way’s gravitational potential. Due to the scarcity of known objects of this type, it is possible that LP 93-21 is the first identified example of a fast-moving, ‘cooled-down’ primary remnant and could represent a missing piece of the SNe Ia/Iax-ejected WD cooling sequence.

Further spectral analysis would provide constraints on the viability of the SNe Ia/Iax scenario in explaining LP 93-21’s observed speed. A detailed spectrum would allow measurements of LP 93-21’s spin and of key elemental abundances that might or might not still be on its surface. More surviving remnants are likely contained within the Gaia data and still need to be found throughout the Milky Way, waiting to help shed light on the SNe Ia/Iax progenitor problem.

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