

Deep and fast Solar System flybys: the controversial case of WD 0810-353

R. de la Fuente Marcos¹ and C. de la Fuente Marcos²

¹ AEGORA Research Group, Facultad de Ciencias Matemáticas, Universidad Complutense de Madrid, Ciudad Universitaria, 28040 Madrid, Spain
e-mail: rauldelafuentemarcos@ucm.es

² Universidad Complutense de Madrid, Ciudad Universitaria, 28040 Madrid, Spain

Received 20 September 2022 / Accepted 9 October 2022

ABSTRACT

Context. Most flybys in the Galactic disk are distant, beyond 10^4 AU, and have characteristic velocities of ~ 70 km s⁻¹. However, deep and fast encounters also take place, albeit with lower probability, particularly if one of the objects involved is a stellar remnant ejected during a supernova. WD 0810-353 might be a high velocity white dwarf, and it was recently identified as heading straight for the Solar System; however, the *Gaia* DR3 data that support its future deep and fast flyby are regarded as suspicious.

Aims. Here, we reanalyze the *Gaia* DR3 data set associated with WD 0810-353 to confirm or reject the reality of its Solar System flyby and also to investigate its possible runaway status.

Methods. We studied the evolution of WD 0810-353 forward in time using *N*-body simulations. We computed the distribution of distances of closest approach and their associated times of perihelion passage. We used a statistical analysis of the kinematics of this object to assess its possible hypervelocity. We compared its mean BP/RP spectrum to those of other well-studied white dwarfs.

Results. We confirm that WD 0810-353 is headed for the Solar System, but the actual parameters of the encounter depend strongly on its radial velocity. The *Gaia* DR3 value of -373.74 ± 8.18 km s⁻¹ is strongly disfavored by our analyses. Its mean BP/RP spectrum suggests a value over ten times higher based on the position of its putative H α line. However, spectral matching using other white dwarfs with non-*Gaia* data indicate a radial velocity in the interval $(-60, -70)$ km s⁻¹.

Conclusions. These results confirm the future flyby of WD 0810-353 near the Solar System, although the relative velocity could be high enough or the minimum approach distance large enough to preclude any significant perturbation on the Oort cloud.

Key words. stars: kinematics and dynamics – white dwarfs – Oort Cloud – methods: data analysis – methods: numerical – celestial mechanics

1. Introduction

Our Sun's journey about the Galactic center leads to stellar flybys in which a star may pass close to the Solar System. In general, stars pass by each other at a comfortable distance (well more than 10^3 to 10^4 AU; see for example Fig. 1 in Hansen 2022), although this may not be the case in star-forming regions (see for example Cuello et al. 2022) or the Galactic bulge (McTier et al. 2020). On the other hand, relative velocities during stellar flybys could be close to or below 1 km s⁻¹ (see for example Table 4 in de la Fuente Marcos & de la Fuente Marcos 2019b) but also as high as 300–3000 km s⁻¹ for objects ejected during supernova explosions (see for example Tomsick et al. 2012; Geier et al. 2015; Tauris 2015; Ruffini & Casey 2019), and 3000–5000 km s⁻¹ for recoil velocities linked to binary black hole mergers (see for example Darbha et al. 2019; Varma et al. 2022).

The average relative speed between two stars selected at random from a Gaussian distribution is given by $v_r = \sqrt{2} \sigma_v$, where σ_v is the velocity dispersion (see for example Mihalas 2003). On the other hand, the velocity dispersion of the Galactic thin disk (where the Sun is located) is 48.9 km s⁻¹ (Anguiano et al. 2020), and this translates into a typical relative speed of Solar System flybys of 69.1 km s⁻¹. Therefore, and in theory, the Solar System may experience close encounters with other objects (stars or collapsed objects) at typical velocities under 100 km s⁻¹ (for a

representative sample, see, for example, Bailer-Jones 2022), but flybys at relative velocities close to or below 1 km s⁻¹ (kinematic siblings of the Sun) or above 1000 km s⁻¹ (hypervelocity objects or runaways) are possible as well.

Using *Gaia* Data Release 3 (DR3) data, Bobylev & Bajkova (2022) find that the white dwarf WD 0810-353 (also known as UPM J0812-3529) will approach the Solar System at a distance of 0.150 ± 0.003 pc in 0.029 ± 0.001 Myr. This is not one of the most remarkable future Solar System flybys in terms of distance of closest approach, but it certainly is the closest in terms of time of perihelion passage among those already studied. This result has been contested by Bailer-Jones (2022), who argues that the value of the radial velocity of WD 0810-353 in *Gaia* DR3 is probably incorrect because radial velocity determinations for white dwarfs from the *Gaia* pipeline are unreliable. In this paper we reanalyze the *Gaia* DR3 data set associated with this object to confirm or reject the reality of its future Solar System flyby as discussed by Bobylev & Bajkova (2022) but also to investigate the possible hypervelocity runaway status of this stellar remnant. This paper is organized as follows. In Sect. 2, we outline the context of our research, review our methodology, and present the data and tools used in our analyses. The controversial nature of the radial velocity of WD 0810-353 is considered in Sect. 3. In Sect. 4, we apply our methodology and, in Sect. 5, discuss its results. Our conclusions are summarized in Sect. 6.

2. Context, methods, and data

In the following, we present some theoretical background useful for navigating the reader through the results presented in the sections, the basic details of our approach and the data, and the tools used to obtain the results.

2.1. Context

Solar System flybys are of interest because it is generally thought that sufficiently close stellar flybys can send small bodies hurtling toward the inner Solar System (see for example [Dybczyński & Królikowska 2022](#)), leading to large-scale impacts on the Earth that may trigger climate change and other harmful large-scale processes (see for example [Collins et al. 2005](#)). One of the first studies aimed at evaluating the probability and parameters of such events was performed by [Mülläri & Orlov \(1996\)](#). [Bailer-Jones et al. \(2018\)](#) used *Gaia* Data Release 2 (DR2) to identify close past and future stellar encounters with the Sun. Using data from *Gaia* and other sources, a number of close stellar encounters with the Solar System have been identified and their characteristic parameters computed (see for example [Bobylev 2010a,b](#); [Bobylev & Bajkova 2017, 2020, 2021, 2022](#); [Wysoczańska et al. 2020](#); [Dybczyński & Breiter 2022](#); [Dybczyński & Królikowska 2022](#); [Dybczyński et al. 2022](#)). Past stellar encounters may have perturbed the Oort cloud (see for example [de la Fuente Marcos & de la Fuente Marcos 2018](#); [de la Fuente Marcos et al. 2018](#)).

The existence of hypervelocity stars was first predicted by [Hills \(1988\)](#) and later discussed by [Yu & Tremaine \(2003\)](#). WD 0810-353 was first identified as a high proper motion white dwarf by [Finch et al. \(2018\)](#), so this object is not a star in a strict sense but rather a stellar remnant; it was further characterized using *Gaia* DR2 data by [Gentile Fusillo et al. \(2019\)](#). Hypervelocity runaway white dwarfs and the mechanisms that produce them have only recently been identified (see for example [Neunteufel 2020](#); [Bauer et al. 2021](#)).

2.2. Methodology

The assessment of the future encounter between WD 0810-353 and the Solar System should be based on an analysis of results from a representative sample of *N*-body simulations that take the uncertainties in the input data from *Gaia* DR3 into account. Here, we carried out such calculations using a direct *N*-body code implemented by [Aarseth \(2003\)](#) that is publicly available from the website of the Institute of Astronomy of the University of Cambridge¹. This software uses the Hermite integration scheme as described by [Makino \(1991\)](#). Results from this code were discussed in detail by [de la Fuente Marcos & de la Fuente Marcos \(2012\)](#). The physical model considers perturbations from: the Sun, the four most massive planets, the barycenter of the Pluto-Charon system, and WD 0810-353 (with an assumed mass of $0.63 M_{\odot}$). This choice is because we are interested in possible effects on Pluto, but Pluto resonant behavior cannot be properly reproduced without Neptune, and Neptune's dynamics cannot be properly simulated without Uranus, Saturn, and Jupiter as the subsystem made of the four giant planets is strongly coupled (see for example [Tanikawa & Ito 2007](#)). Our calculations do not include the Galactic potential as they consist of integrations forward in time for short timescales, while the Sun takes ~ 220 Myr to complete one revolution around the center of the Galaxy. Our approach has already been used within

the context of studying stellar encounters ([de la Fuente Marcos & de la Fuente Marcos 2018, 2020, 2022](#)).

2.3. Data, data sources, and tools

Gaia DR3 ([Gaia Collaboration 2016, 2022](#)) provides, among other data, right ascension and declination, absolute stellar parallax, proper motions in right ascension and declination (all referred to epoch 2016.0 or 2457388.5 TDB, Barycentric Dynamical Time), spectroscopic radial velocity, and their respective standard errors for over 3.38×10^7 sources, all in the solar barycentric reference frame. These data can be transformed into equatorial values as described by [Johnson & Soderblom \(1987\)](#), and state vectors in the ecliptic and mean equinox of reference epoch suitable for Solar System numerical integrations can be computed by applying the usual transformation that involves the obliquity. Here, we used input data from *Gaia* DR3 and barycentric Cartesian state vectors for the Solar System – provided by Jet Propulsion Laboratory's HORIZONS ([Giorgini 2015](#))², based on the new DE440/441 planetary ephemeris ([Park et al. 2021](#)), and retrieved using resources from the Python package Astroquery ([Ginsburg et al. 2019](#)). Figures were produced using the Matplotlib library ([Hunter 2007](#)) and statistical tools provided by NumPy ([Harris et al. 2020](#)).

In order to compute the galactocentric Galactic velocity components, we used the software pipeline described by [de la Fuente Marcos & de la Fuente Marcos \(2019a\)](#). Galactocentric positions were found using the value of the distance between the Sun and the Galactic center (Sgr A*) given by [GRAVITY Collaboration \(2019\)](#), 8.18 kpc. The galactocentric standard of rest is a right-handed coordinate system centered at the Galactic center with positive axes in the directions of the Galactic center (away from it), Galactic rotation, and the North Galactic Pole as discussed by [Johnson & Soderblom \(1987\)](#), for example. Galactocentric Galactic velocity components were calculated as described by [Johnson & Soderblom \(1987\)](#), considering the solar motion values computed by [Schönrich et al. \(2010\)](#) and the value of the in-plane circular motion of the local standard of rest around the Galactic center discussed by [Reid et al. \(2014\)](#).

3. Caveats of the radial velocity value of WD 0810-353

In addition to being a putative close approach in the astrophysically near future, WD 0810-353 is a DA magnetic white dwarf with a very strong magnetic field (perhaps as high as 30 MG), a mass of $0.63 M_{\odot}$, and an age (obtained by interpolation in the cooling curve) of 2.7 Gyr ([Bagnulo & Landstreet 2020](#)). In principle, *Gaia* DR3 ([Gaia Collaboration 2016, 2022](#)) provides robust data for this interesting object. WD 0810-353 is designated *Gaia* DR3 5544743925212648320 and has a parallax of 89.5064 ± 0.0155 mas, proper motions in right ascension of -65.479 ± 0.016 mas yr⁻¹ and declination of -29.204 ± 0.018 mas yr⁻¹, and a radial velocity of -373.74 ± 8.18 km s⁻¹ with a renormalized unit weight error (RUWE) of 1.039.

If RUWE > 1.4, the relevant astrometric solution could be problematic and may produce inaccurate results³. However, [Stassun & Torres \(2021\)](#) have pointed out that RUWE values

¹ <https://www.ast.cam.ac.uk/~sverre/web/pages/nbody.htm>

² <https://ssd.jpl.nasa.gov/?horizons>

³ https://gea.esac.esa.int/archive/documentation/GDR2/Gaia_archive/chap_datamodel/sec_dm_main_tables/ssc_dm_ruwe.html

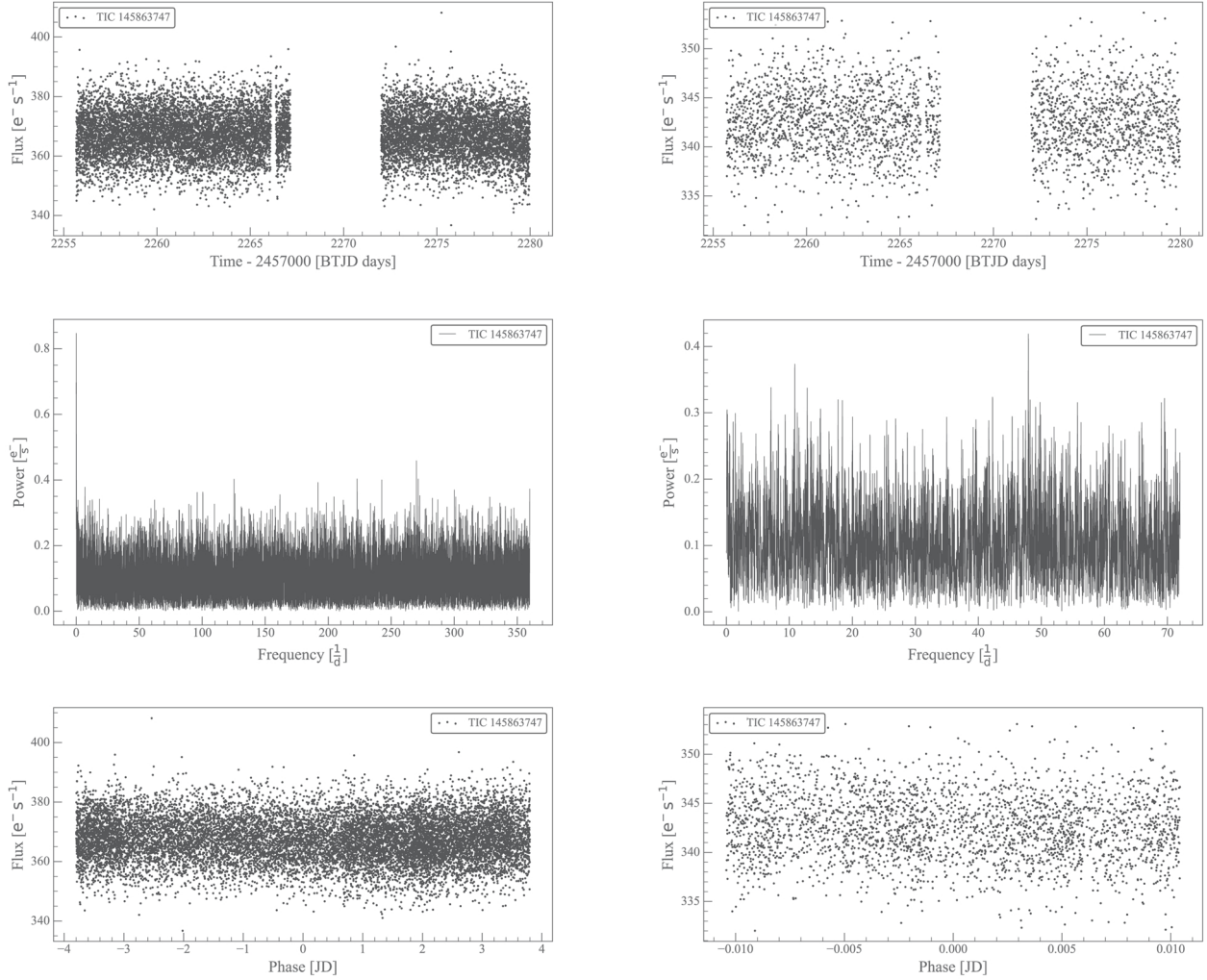


Fig. 1. TESS light curve of TIC 145863747 (=WD 0810-353). *Left panels:* target originally observed at a 120 s cadence. *Right panels:* in the extended TESS mission the full frame image cadence is reduced to 600 s. *Top panels:* light curve plotted with the tool Lightcurve, a Python package for Kepler and TESS data analysis (Lightcurve Collaboration 2018; Dotson et al. 2019). *Middle panels:* periodogram computed by Lightcurve. *Bottom panels:* phased light curve computed by Lightcurve. Both observations include a significant data gap, in each case caused by the Earth rising above the sunshade on the spacecraft and contributing significant scattered light.

even slightly above 1.0 may signal unresolved binaries in *Gaia* data. WD 0810-353 has also been observed by the Transiting Exoplanet Survey Satellite (TESS) mission (Ricker et al. 2015) as TIC 145863747 (Guerrero et al. 2021). Data from TESS are available at the Mikulski Archive for Space Telescopes (MAST)⁴. The target was observed in Sector 35 in 2021, with light curves extracted from TESS full frame image data. According to light curve data from TESS (see Fig. 1), the object is not variable and as such appears to be a single source, which is consistent with its RUWE of 1.039 from *Gaia* DR3.

The high value of the radial velocity of WD 0810-353 makes it an outlier among the population of known white dwarfs in the solar neighborhood (see for example Hollands et al. 2018; McCleery et al. 2020) and may qualify it as a member of an even more exclusive class of objects, the hypervelocity runaway white dwarfs. Hypervelocity runaway white dwarfs can be produced as a result of Type Ia supernovae (Vennes et al. 2017). Survivors are ejected from compact binaries with velocities close to 600 km s⁻¹ or higher, and they might become unbound from

their progenitor galaxies (Raddi et al. 2018a,b). On their way out, they may experience flybys with other stars and their planetary systems, as argued by Bobylev & Bajkova (2022). In the Milky Way, there are at least four known hypervelocity runaway white dwarfs (Raddi et al. 2019). However, the critical question here is whether the value of the radial velocity of WD 0810-353 in *Gaia* DR3 can be trusted or not.

The Radial Velocity Spectrometer (RVS) is a near-infrared (847–874 nm) instrument with a medium resolution (resolving power of 11 500); the wavelength range works best for G- and K-type stars, and for them radial velocities are derived using three strong ionized calcium lines found at around 849.8, 854.2, and 855.2 nm (Katz et al. 2019). For stars fainter than $G_{\text{RVS}} = 12$ mag (WD 0810-353 has $G_{\text{RVS}} = 13.67$ mag), the *Gaia* DR3 pipeline derives the radial velocity via the cross-correlation of the observed *Gaia*-RVS spectra with a synthetic template. Unfortunately, the pipeline does not contain templates for white dwarfs; a template with certain atmospheric parameters (effective temperature, surface gravity, and metallicity) is used instead. For WD 0810-353, $T_{\text{eff}} = 6000$ K, $\log g = 4.5$, and $[\text{Fe}/\text{H}] = -1.5$ dex were used. It is most likely that this

⁴ <https://archive.stsci.edu/teess/>

template is inappropriate for a white dwarf. The impact of such a template mismatch on the radial velocity has not yet been characterized, but the use of inconsistent templates for other object types, for example emission line stars, has led to systematic errors of several hundred km s^{-1} (Katz et al. 2022).

In order to quantify the impact of using inadequate templates to compute the radial velocities of white dwarfs in *Gaia* DR3, we investigated how many white dwarfs have *Gaia* DR3 radial velocities that are in agreement with non-*Gaia* values from the literature. This analysis would not unambiguously prove that the specific radial velocity of WD 0810-353 is valid, but would provide reassurances regarding the ability of the *Gaia* DR3 pipeline to measure the radial velocities of some white dwarfs despite the lack of an appropriate template in the pipeline. Our master list of white dwarfs was collected from the SIMBAD⁵ astronomical database (Wenger et al. 2000) using the Simbad module from the Python package Astroquery to query the Simbad service. There are 44 457 sources in SIMBAD catalogued as white dwarfs. Out of this sample, 19 638 have radial velocities from the literature (some but not many of them from *Gaia* DR2). Out of this smaller sample, 114 have both radial velocity values in SIMBAD (41 from *Gaia* DR2) and *Gaia* DR3. The correlation between the two sets of values for this smaller sample is shown in Fig. 2. Therefore, it is true that some non-*Gaia* radial velocities correlate well with their associated *Gaia* DR3 values, but, in general, the correlation is not statistically significant. However, for the outlier white dwarf LB 3209, the SIMBAD value is $+338.3 \pm 2.1 \text{ km s}^{-1}$ and the *Gaia* DR3 measurement is $+424 \pm 30 \text{ km s}^{-1}$, which means that there is a marginal agreement between the two values at the 2.9σ level.

The *Gaia* DR3 pipeline computes radial velocities by studying the positions of one or more spectral lines. In the case of white dwarfs, their rather flat spectra provide few lines useful for this task. One of them is the 656.3 nm (first Balmer, in air) line of hydrogen ($\text{H}\alpha$). In addition to astrometry and radial velocities, *Gaia* DR3 provides BP/RP externally calibrated sampled mean spectra (the low-resolution XP spectra in the wavelength range 330–1050 nm) for 219 197 643 sources (De Angeli et al. 2022; Montegriffo et al. 2022). WD 0810-353 and LB 3209 are part of this sample. Figure 3 shows the *Gaia* DR3 spectra (normalized so they all have 1 as the relative flux at 550 nm) of three white dwarfs: WD 0810-353, LB 3209, and UCAC4 398-010797. For LB 3209 (RUWE = 0.951), the $\text{H}\alpha$ appears redshifted and its position is consistent with that expected for the SIMBAD value of $+338.3 \pm 2.1 \text{ km s}^{-1}$. White dwarf LB 3209 is the conspicuous outlier in Fig. 2. On the other hand, if the absorption feature observed in the spectrum of WD 0810-353 at about 647 nm is a blueshifted $\text{H}\alpha$, then the associated radial velocity is close to -4300 km s^{-1} . If this interpretation is correct, the *Gaia* DR3 value of $-373.74 \pm 8.18 \text{ km s}^{-1}$ is wrong. We have to emphasize here that the resolving power of the *Gaia* DR3 XP spectra (not the RVS spectra) is regarded as too low to measure a radial velocity that could be compared to values from the literature. However, the case of LB 3209 is intriguing as the RVS value, the SIMBAD value, and the one derived from the XP spectrum are all somewhat consistent.

Figure 3 also shows the low-resolution *Gaia* DR3 mean BP/RP spectrum of UCAC4 398-010797 (RUWE = 1.053), which seems to be a very close match for WD 0810-353 in the displayed wavelength interval. White dwarf UCAC4 398-010797 also has a high proper motion in *Gaia* DR3 (proper motions in right ascension of $-64.18 \pm 0.02 \text{ mas yr}^{-1}$ and declination

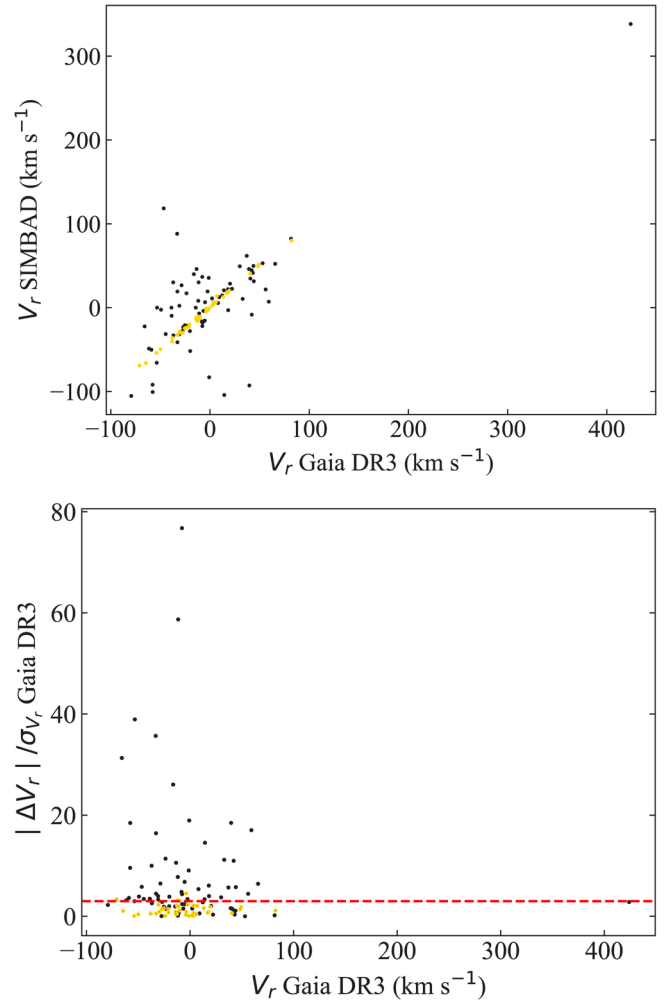


Fig. 2. Correlation between radial velocity values of white dwarfs in SIMBAD and *Gaia* DR3. *Top panel:* SIMBAD radial velocity as a function of the corresponding *Gaia* DR3 value. *Bottom panel:* absolute value of the difference between the SIMBAD and the *Gaia* DR3 values divided by the uncertainty in the *Gaia* DR3 value. The dashed red line signals the 3σ difference. Points in gold signal SIMBAD values from *Gaia* DR2.

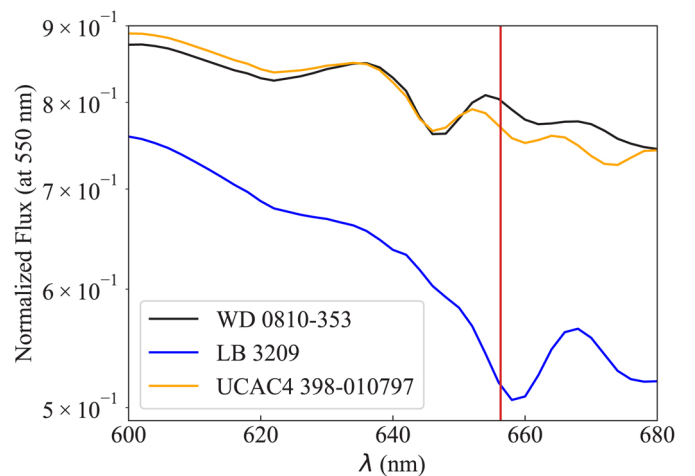


Fig. 3. Low-resolution *Gaia* DR3 mean BP/RP spectra of WD 0810-353, LB 3209, and UCAC4 398-010797. For reference, the vertical red line marks the position of the $\text{H}\alpha$ line at rest (656.3 nm).

⁵ <https://simbad.cds.unistra.fr/simbad/>

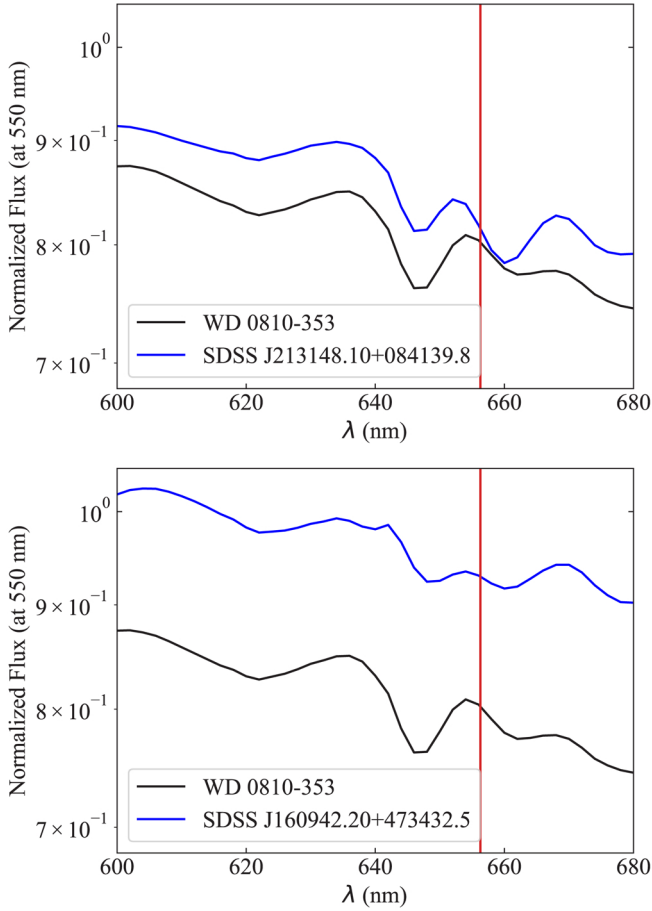


Fig. 4. Low-resolution *Gaia* DR3 mean BP/RP spectra of spectral analogs of WD 0810-353. *Top panel:* SDSS J213148.10+084139.8. *Bottom panel:* SDSS J160942.20+473432.5. For reference, the vertical red line marks the position of the $H\alpha$ line at rest (656.3 nm).

of -152.84 ± 0.02 mas yr $^{-1}$), but it has no radial velocity. The spectrum of UCAC4 398-010797 tells us that WD 0810-353 is not unique and that if the absorption feature in the spectrum of WD 0810-353 is a blueshifted $H\alpha$ then UCAC4 398-010797 may also be approaching at a speed close to 4000 km s $^{-1}$. It is certainly very unusual to find one object with such a high speed approaching the Solar System, but finding two such objects strongly suggests that the absorption feature discussed above may not be a blueshifted $H\alpha$.

In order to further clarify the status of objects such as WD 0810-353 and UCAC4 398-010797, we studied the sample of white dwarfs with a non-*Gaia* radial velocity in SIMBAD and the XP spectrum that resembles that of WD 0810-353. Two such objects are SDSS J213148.10+084139.8 and SDSS J160942.20+473432.5 (see Fig. 4). White dwarf SDSS J213148.10+084139.8 has a radial velocity in SIMBAD of -63 ± 3 km s $^{-1}$ and -39 ± 11 km s $^{-1}$ in *Gaia* DR3; SDSS J160942.20+473432.5 has respective values of -23 ± 2 km s $^{-1}$ and -21.3 ± 1.2 km s $^{-1}$. For SDSS J213148.10+084139.8 the two values are consistent at the 2.2σ level; for SDSS J160942.20+473432.5 consistency is at the 1.4σ level. Both cases suggest that the absorption feature in the spectrum of WD 0810-353 is not $H\alpha$ and that the actual radial velocity of WD 0810-353 could be a relatively normal value well below -100 km s $^{-1}$.

4. Results

Here, we first used *Gaia* DR3 data to investigate the possible hypervelocity runaway nature of this stellar remnant and to reproduce the details of the future flyby of WD 0810-353 near the Solar System as discussed by Bobylev & Bajkova (2022). However, and as pointed out above, the value of the radial velocity of WD 0810-353 in *Gaia* DR3 could be incorrect, and alternative scenarios, namely the extreme hypervelocity case and one standard flyby, are discussed as well.

4.1. Hypervelocity runaway white dwarf

Using the approach described above, we computed both the galactocentric distance and velocity for WD 0810-353; we also found the angle between the position and velocity vectors. As is customary in *Gaia*-related publications, we provide the median (50th percentile) and the 16th and 84th percentiles (as the quality of the published data is very good, the dispersion is small and symmetrical). The galactocentric velocity is $v_{GC} = 617 \pm 8$ km s $^{-1}$, and the angle is $\theta = 101.16^\circ \pm 0.10^\circ$; the galactocentric Galactic velocity components are $U = 119 \pm 2$ km s $^{-1}$, $V = 605 \pm 8$ km s $^{-1}$, and $W = 8.7 \pm 0.4$ km s $^{-1}$. Deason et al. (2019) find a value for the escape speed in the neighborhood of the Sun of 528^{+24}_{-25} km s $^{-1}$. Therefore, and for the value of the radial velocity in *Gaia* DR3, WD 0810-353 may already be unbound to the Milky Way at the 3.6σ level. If we consider the effect of Einstein's gravitational redshift and perform the correction pointed out above, the values are: $v_{GC} = 667 \pm 8$ km s $^{-1}$, $\theta = 101.59^\circ \pm 0.09^\circ$, $U = 133 \pm 2$ km s $^{-1}$, $V = 653 \pm 8$ km s $^{-1}$, and $W = 9.4 \pm 0.4$ km s $^{-1}$. WD 0810-353 is moving tangentially, and the value of the angle is in the neighborhood of 90° as both vectors are nearly perpendicular, which is often interpreted as suggestive of an extragalactic origin if unbound. However, the relatively low estimated age of WD 0810-353 as given by Bagnulo & Landstreet (2020) helps in discarding a possible intergalactic provenance. The trajectory has a small inclination with respect to the disk, so it was probably ejected from the thick or even the thin disk.

4.2. Solar System flyby

Figure 5 shows the results of 10^5 integrations of control orbits of WD 0810-353 generated using input data from *Gaia* DR3. In order to confirm or reject the results obtained by Bobylev & Bajkova (2022), we focused on providing an estimate of the value of the distance of closest approach and its associated time of perihelion passage. The distribution of times is shown in the top-left panel: the mean and standard deviation are 0.0292 ± 0.0006 Myr, the median value is 0.0292 Myr, and 0.0282–0.0303 Myr is the 90% confidence interval. The distribution of distances of closest approach in the top-right panel has a mean and standard deviation of 0.114 ± 0.002 pc (or $23\,424 \pm 514$ AU, median of 23 412 AU) with a 90% probability of coming within 0.110–0.118 pc (<0.120 pc, 99%). This places WD 0810-353 well inside the Oort cloud (see for example Oort 1950). The bottom panels of Fig. 5 show that faster approaches tend to produce earlier and closer flybys. However, the effects of the flyby on the orbit of the Pluto-Charon system (and therefore, on the classical trans-Neptunian belt) are still negligible. Our results are consistent with those in Bobylev & Bajkova (2022) and Bailer-Jones (2022).

Considering the effect of Einstein's gravitational redshift (Greenstein & Trimble 1967) on the value of the radial

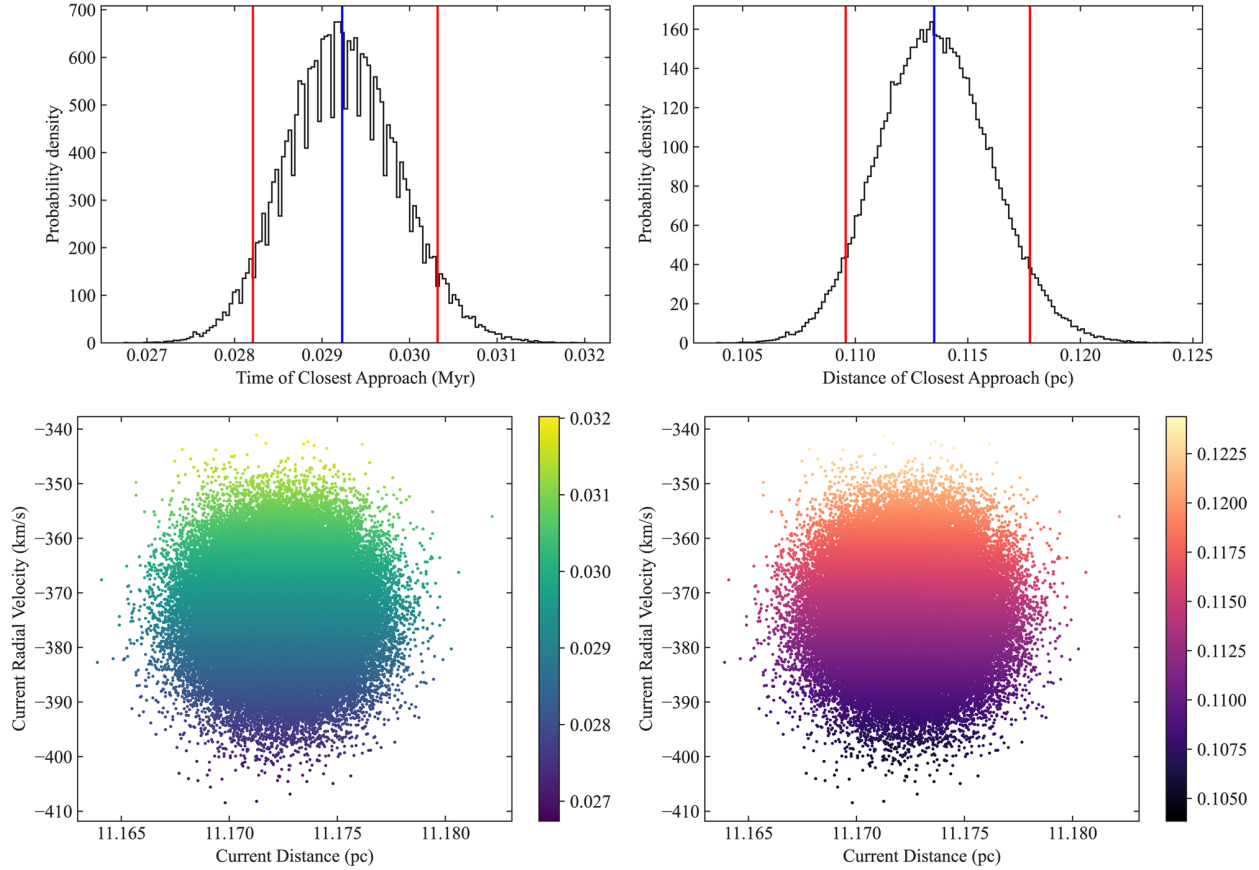


Fig. 5. Future perihelion passage of WD 0810-353 as estimated from *Gaia* DR3 input data and the *N*-body simulations discussed in the text without accounting for the effect of Einstein’s gravitational redshift. The distribution of times of perihelion passage is shown in the *top-left panel* and perihelion distances in the *top-right one*. The blue vertical lines mark the median values, and the red ones show the 5th and 95th percentiles. The *bottom panels* show the times of perihelion passage in megayears (*bottom left*) and the distance of closest approach in parsecs (*bottom right*) as a function of the observed values of the radial velocity of WD 0810-353 and its distance (randomly generated using the mean values and standard deviations from *Gaia* DR3), both as color-coded scatter plots of the distribution in the associated top panel. Histograms were produced using the Matplotlib library (Hunter 2007) with sets of bins computed using Astropy (Astropy Collaboration 2013, 2018) by applying the Freedman and Diaconis rule (Freedman & Diaconis 1981); instead of considering frequency-based histograms, we used counts to form a probability density such that the area under the histogram sums to one. The color map scatter plot was also produced using Matplotlib.

velocity (so it becomes $-423.74 \pm 8.18 \text{ km s}^{-1}$) as pointed out by Bobylev & Bajkova (2022) leads to similar values (see Fig. 6). In this case, the distribution of distances of closest approach has a median value of 0.100 pc with a 90% probability of coming within 0.097–0.103 pc of the Sun; the associated time of perihelion passage is determined to be between 0.0250 and 0.0266 Myr with 90% confidence, with a most likely value of 0.0258 Myr.

4.3. Alternative scenarios

Under the assumption that WD 0810-353 has a radial velocity of $-4248 \pm 457 \text{ km s}^{-1}$, as discussed in Sect. 3, Fig. 7 shows the results of 10^5 integrations of control orbits of WD 0810-353. In this case, the distribution of distances of closest approach has a median value of 0.015 pc (or 3094 AU) with a 90% probability of coming within 0.010–0.023 pc of the Sun; the associated time of perihelion passage is determined to be between 0.0022 and 0.0031 Myr with 90% confidence, with a most likely value of 0.0026 Myr. On the other hand, when a radial velocity of $-63 \pm 3 \text{ km s}^{-1}$ is considered, a distant encounter at 6.35 pc takes place in 0.075 Myr (see Fig. 8). As pointed out in the previous section, the faster the approach, the deeper the flyby.

5. Discussion

Using the data in *Gaia* DR3 as input, our analyses confirm that the magnetic white dwarf WD 0810-353 will experience a near-future close encounter with the Solar System and that it is a probable member of a very exotic group of objects, the hypervelocity runaway white dwarfs. The question then arises as to how we know if it is a survivor of a peculiar thermonuclear supernova. The prototype of this class of unusual objects is LP 40-365, which has a rather peculiar spectral appearance (see Figs. 1 and 4 in Raddi et al. 2018a). A detailed plot of the XP spectrum of WD 0810-353 (see Sect. 3) is shown in Fig. 9, and it closely resembles that of LP 40-365 in Figs. 1 and 4 of Raddi et al. (2018a). We therefore conclude that, if the radial velocity of WD 0810-353 in *Gaia* DR3 is not spurious (but see Sect. 3), the nature (both physical and dynamical) of WD 0810-353 could be very similar to that of LP 40-365, which is also unbound to the Galaxy.

However, our discussion in Sect. 3 and our initial comment in Sect. 1 both suggest that a flyby at a relative velocity close to 70 km s^{-1} is far more likely, although it will lead to an unremarkable close encounter. The analyses in Sect. 3 also show the potential of *Gaia*’s XP spectra to reproduce (albeit with lower

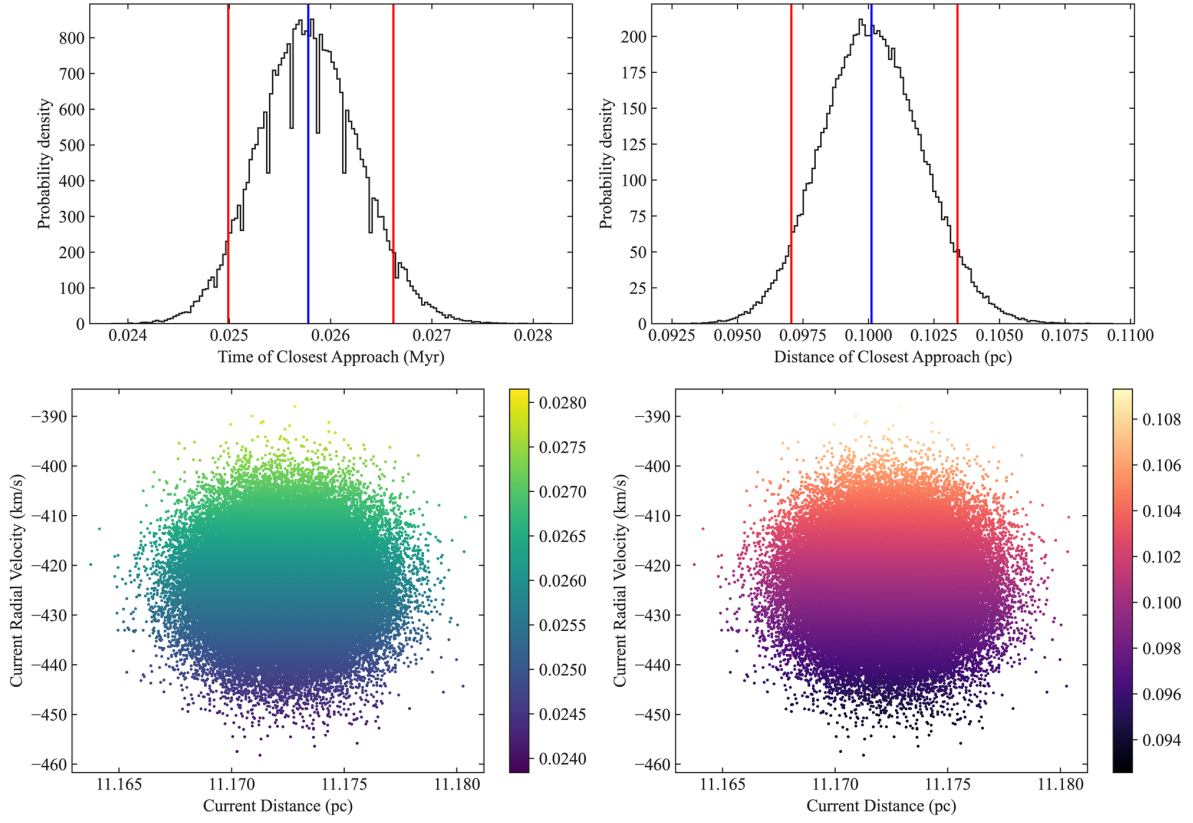


Fig. 6. Same as Fig. 5 but considering the effect of Einstein’s gravitational redshift (Greenstein & Trimble 1967) on the value of the radial velocity (so it becomes $-423.74 \pm 8.18 \text{ km s}^{-1}$), as pointed out by Bobylev & Bajkova (2022). The blue vertical lines mark the median values, and the red ones show the 5th and 95th percentiles.

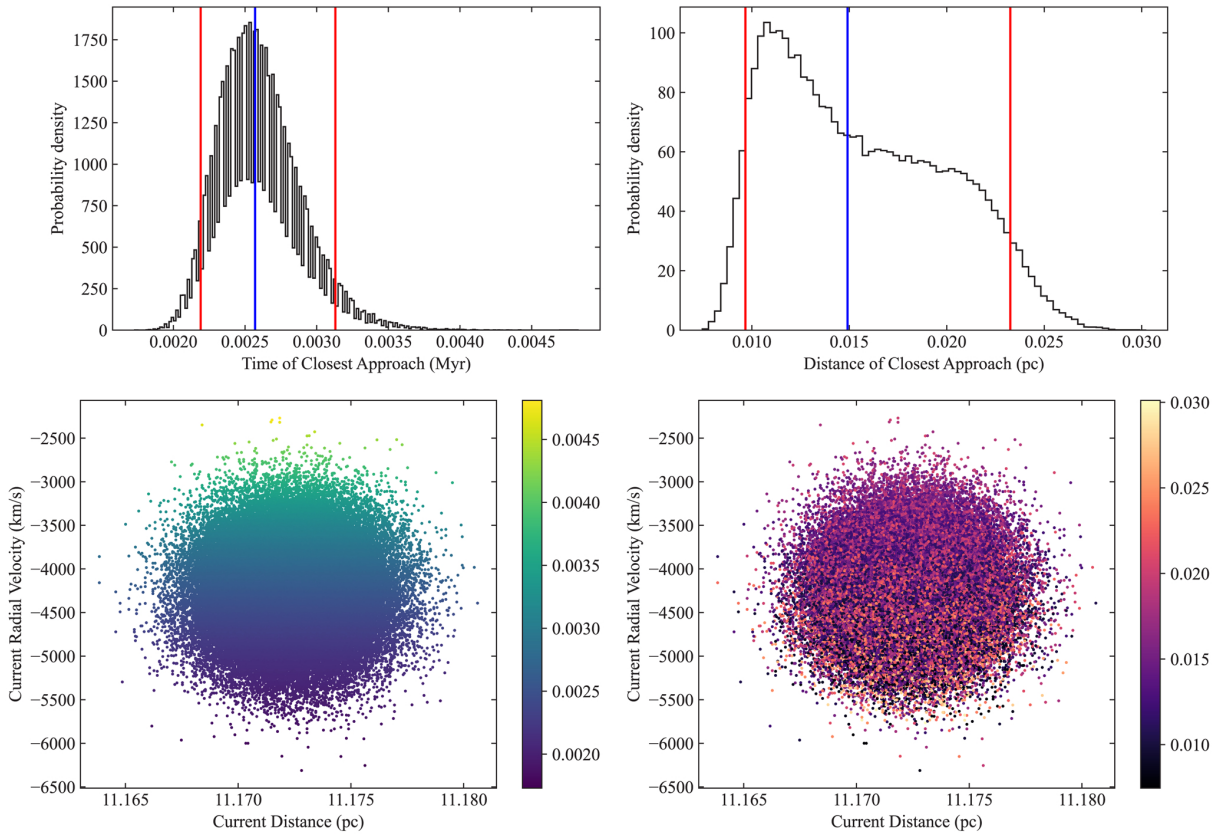


Fig. 7. Same as Fig. 5 but assuming a radial velocity of $-4248 \pm 457 \text{ km s}^{-1}$, as discussed in Sect. 3. The blue vertical lines mark the median values, and the red ones show the 5th and 95th percentiles.

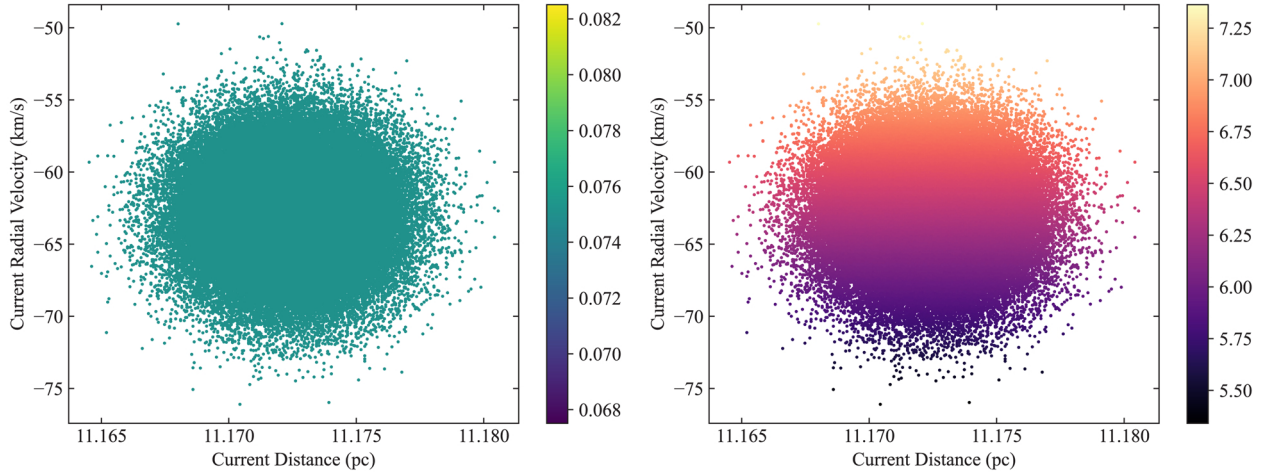


Fig. 8. Same as the *bottom panels* of Fig. 5, but assuming a radial velocity of $-63 \pm 3 \text{ km s}^{-1}$, as discussed in Sect. 3.

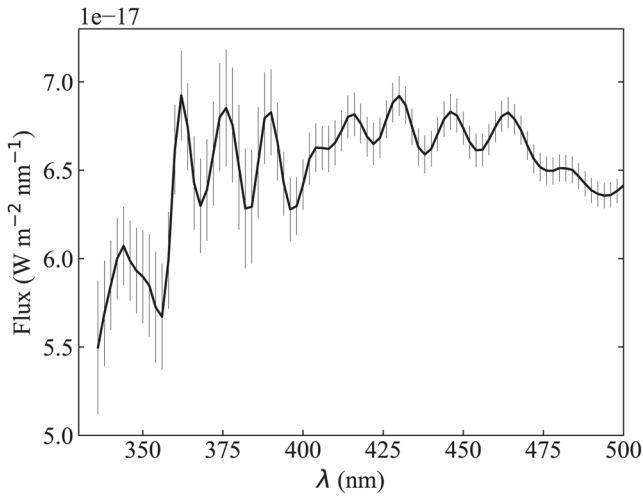


Fig. 9. Detail of the low-resolution mean BP/RP spectrum of WD 0810-353. This part of the spectrum closely resembles that of LP 40-365 in Figs. 1 and 4 of Raddi et al. (2018a).

quality) radial velocity results from the literature but also to uncover candidates with unusual kinematics, particularly when *Gaia* Data Release 4 is released as it will feature a much more extensive radial velocity catalog. In the absence of other data, the low-resolution XP spectra indeed appear to have the potential to allow the preliminary identification of sources with unusual redshifts or blueshifts suitable for further study at higher spectral resolutions.

6. Summary and conclusions

In this paper we made use of input data from *Gaia* DR3 to study the evolution of the magnetic white dwarf WD 0810-353 forward in time using direct *N*-body simulations and factoring the uncertainties into the calculations. In addition, we explored a tentative connection between WD 0810-353 and the small group of known hypervelocity runaway white dwarfs using both astrometric and spectroscopic *Gaia* DR3 data. We also performed a detailed comparison between the values of the radial velocity of white dwarfs from the literature and from *Gaia* DR3,

providing a list of relevant caveats to be considered when dealing with *Gaia* DR3 radial velocity data. Our conclusions can be summarized as follows.

1. In general, radial velocity determinations for white dwarfs in *Gaia* DR3 may be incorrect. This is due to the lack of synthetic white dwarf templates in the RVS pipeline. However, we have found a number of examples in which the values from the literature are statistically consistent with those from *Gaia* DR3, including the outlier LB 3209.
2. We confirm that WD 0810-353 is single and not variable within the uncertainties associated with TESS data.
3. We confirm that WD 0810-353 will experience a near-future Solar System flyby with the following parameters (average and standard deviation): a minimum approach distance of $0.114 \pm 0.002 \text{ pc}$ and a time of perihelion passage of $0.0292 \pm 0.0006 \text{ Myr}$. The relative velocity will be high enough to preclude any significant perturbation on the Oort cloud. This conclusion is valid if the value of the radial velocity of this white dwarf in *Gaia* DR3 is not spurious.
4. Considering the data at face value, we find that WD 0810-353 could be a hypervelocity runaway white dwarf as the value of its *V* component is above 600 km s^{-1} , which is typical for ejected thermonuclear supernova survivors.
5. Again assuming a correct value of the radial velocity in *Gaia* DR3 and considering the value for the escape speed in the neighborhood of the Sun, WD 0810-353 may already be unbound to the Milky Way. An origin in the Galactic disk is favored.
6. The analysis of the low-resolution mean BP/RP spectrum of WD 0810-353 shows that it is a reasonable match for LP 40-365.
7. If the radial velocity of WD 0810-353 in *Gaia* DR3 is spurious, our calculations show that an average radial velocity leads to an unremarkable flyby. If an absorption feature in the XP spectrum of this object is the $H\alpha$ line, then it may be an extreme hypervelocity white dwarf that will experience a deep and exceptionally fast flyby with the Solar System a few thousand years from now.

Given the potential importance of WD 0810-353, an independent radial velocity determination for this object will put an end to this controversy and improve our practical understanding of how reliable the radial velocity determinations for white dwarfs in *Gaia* DR3 are.

Acknowledgements. We thank three anonymous reviewers for input (one of them was particularly informative and the current form of this work owes a great deal to the recommendations in this second review), S.J. Aarseth for providing one of the codes used in this research, S. Deen for suggesting UCAC4 398-010797 as a spectral analog for WD 0810-353, and A.I. Gómez de Castro for providing access to computing facilities. This work was partially supported by the Spanish ‘Agencia Estatal de Investigación (Ministerio de Ciencia e Innovación)’ under grant PID2020-116726RB-I00 /AEI/10.13039/501100011033. In preparation of this paper, we made use of the NASA Astrophysics Data System and the ASTRO-PH e-print server. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. This work has made use of data from the European Space Agency (ESA) mission *Gaia* (<https://www.cosmos.esa.int/gaia>), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, <https://www.cosmos.esa.int/web/gaia/dpac/consortium>). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

References

- Aarseth, S. J. 2003, *Gravitational N-Body Simulations* (Cambridge: Cambridge University Press), 27
- Anguiano, B., Majewski, S. R., Hayes, C. R., et al. 2020, *AJ*, **160**, 43
- Astropy Collaboration (Robitaille, T. P., et al.) 2013, *A&A*, **558**, A33
- Astropy Collaboration (Price-Whelan, A. M., et al.) 2018, *AJ*, **156**, 123
- Bagnulo, S., & Landstreet, J. D. 2020, *A&A*, **643**, A134
- Bailer-Jones, C. A. L. 2022, *ApJ*, **935**, L9
- Bailer-Jones, C. A. L., Rybizki, J., Andrae, R., et al. 2018, *A&A*, **616**, A37
- Bauer, E. B., Chandra, V., Shen, K. J., et al. 2021, *ApJ*, **923**, L34
- Bobylev, V. V. 2010a, *Astron. Lett.*, **36**, 220
- Bobylev, V. V. 2010b, *Astron. Lett.*, **36**, 816
- Bobylev, V. V., & Bajkova, A. T. 2017, *Astron. Lett.*, **43**, 559
- Bobylev, V. V., & Bajkova, A. T. 2020, *Astron. Lett.*, **46**, 245
- Bobylev, V. V., & Bajkova, A. T. 2021, *Astron. Lett.*, **47**, 180
- Bobylev, V., & Bajkova, A. 2022, *Astron. Lett.*, submitted [arXiv:2206.14443]
- Collins, G. S., Melosh, H. J., & Marcus, R. A. 2005, *Meteorit. Planet. Sci.*, **40**, 817
- Cuello, N., Ménard, F., & Price, D. J. 2022, *Eur. Phys. J. Plus*, in press [arXiv:2207.09752]
- Darbha, S., Coughlin, E. R., Kasen, D., et al. 2019, *MNRAS*, **482**, 2132
- De Angeli, F., Weiler, M., Montegriffo, P., et al. 2022, *A&A*, submitted, <https://doi.org/10.1051/0004-6361/202243680>
- Deason, A. J., Fattahi, A., Belokurov, V., et al. 2019, *MNRAS*, **485**, 3514
- de la Fuente Marcos, C., & de la Fuente Marcos, R. 2012, *MNRAS*, **427**, 728
- de la Fuente Marcos, R., & de la Fuente Marcos, C. 2018, *RNAAS*, **2**, 30
- de la Fuente Marcos, R., & de la Fuente Marcos, C. 2019a, *A&A*, **627**, A104
- de la Fuente Marcos, C., & de la Fuente Marcos, R. 2019b, *MNRAS*, **489**, 951
- de la Fuente Marcos, R., & de la Fuente Marcos, C. 2020, *RNAAS*, **4**, 222
- de la Fuente Marcos, R., & de la Fuente Marcos, C. 2022, *RNAAS*, **6**, 136
- de la Fuente Marcos, C., de la Fuente Marcos, R., & Aarseth, S. J. 2018, *MNRAS*, **476**, L1
- Dotson, J., Barentsen, G., Hedges, C. L., et al. 2019, *AAS Meeting #233*, 445.01
- Dybczyński, P. A., & Breiter, S. 2022, *A&A*, **657**, A65
- Dybczyński, P. A., & Królikowska, M. 2022, *A&A*, **660**, A100
- Dybczyński, P. A., Berski, F., Tokarek, J., et al. 2022, *A&A*, **664**, A123
- Finch, C. T., Zacharias, N., & Jao, W.-C. 2018, *AJ*, **155**, 176
- Freedman, D., & Diaconis, P. 1981, *Z. Wahrscheinlichkeitstheor. verwandte Geb.*, **57**, 453
- Gaia Collaboration (Prusti, T., et al.) 2016, *A&A*, **595**, A1
- Gaia Collaboration (Vallenari, A., et al.) 2022, *A&A*, in press
- Geier, S., Fürst, F., Ziegerer, E., et al. 2015, *Science*, **347**, 1126
- Gentile Fusillo, N. P., Tremblay, P.-E., Gänsicke, B. T., et al. 2019, *MNRAS*, **482**, 4570
- Ginsburg, A., Sipőcz, B. M., Brasseur, C. E., et al. 2019, *AJ*, **157**, 98
- Giorgini, J. D. 2015, *IAUGA*, **22**, 2256293
- GRAVITY Collaboration (Abuter, R., et al.) 2019, *A&A*, **625**, A10
- Greenstein, J. L., & Trimble, V. L. 1967, *ApJ*, **149**, 283
- Guerrero, N. M., Seager, S., Huang, C. X., et al. 2021, *ApJS*, **254**, 39
- Hansen, B. M. S. 2022, *AJ*, **163**, 44
- Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, *Nature*, **585**, 357
- Hills, J. G. 1988, *Nature*, **331**, 687
- Hollands, M. A., Tremblay, P.-E., Gänsicke, B. T., et al. 2018, *MNRAS*, **480**, 3942
- Hunter, J. D. 2007, *Comput. Sci. Eng.*, **9**, 90
- Johnson, D. R. H., & Soderblom, D. R. 1987, *AJ*, **93**, 864
- Katz, D., Sartoretti, P., Cropper, M., et al. 2019, *A&A*, **622**, A205
- Katz, D., Sartoretti, P., Guerrier, A., et al. 2022, *A&A*, submitted [arXiv:2206.05902]
- Landstreet, J. D., Bagnulo, S., Valyavin, G. G., et al. 2012, *A&A*, **545**, A30
- Lightcurve Collaboration (Cardoso, J. V. de M., et al.) 2018, *Astrophysics Source Code Library* [record ascl:1812.013]
- Makino, J. 1991, *ApJ*, **369**, 200
- McCleery, J., Tremblay, P.-E., Gentile Fusillo, N. P., et al. 2020, *MNRAS*, **499**, 1890
- McTier, M. A. S., Kipping, D. M., & Johnston, K. 2020, *MNRAS*, **495**, 2105
- Mihos, J. C. 2003, in *Carnegie Observatories Astrophysics Series*, **3**, Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution, eds. J. S. Mulchaey, A. Dressler, & A. Oemler (Cambridge: Cambridge University Press)
- Montegriffo, P., De Angeli, F., Andrae, R., et al. 2022, *A&A*, in press
- Mülläri, A. A., & Orlov, V. V. 1996, *Earth Moon and Planets*, **72**, 19
- Neunteufel, P. 2020, *A&A*, **641**, A52
- Oort, J. H. 1950, *Bull. Astron. Inst. Netherlands*, **11**, 91
- Park, R. S., Folkner, W. M., Williams, J. G., et al. 2021, *AJ*, **161**, 105
- Raddi, R., Hollands, M. A., Koester, D., et al. 2018a, *ApJ*, **858**, 3
- Raddi, R., Hollands, M. A., Gänsicke, B. T., et al. 2018b, *MNRAS*, **479**, L96
- Raddi, R., Hollands, M. A., Koester, D., et al. 2019, *MNRAS*, **489**, 1489
- Reid, M. J., Menten, K. M., Brunthaler, A., et al. 2014, *ApJ*, **783**, 130
- Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2015, *J. Astron. Telescopes Instrum. Syst.*, **1**, 014003
- Ruffini, N. J., & Casey, A. R. 2019, *MNRAS*, **489**, 420
- Schönrich, R., Binney, J., & Dehnen, W. 2010, *MNRAS*, **403**, 1829
- Stassun, K. G., & Torres, G. 2021, *ApJ*, **907**, L33
- Tanikawa, K., & Ito, T. 2007, *PASJ*, **59**, 989
- Tauris, T. M. 2015, *MNRAS*, **448**, L6
- Tomsick, J. A., Bodaghee, A., Rodriguez, J., et al. 2012, *ApJ*, **750**, L39
- Varma, V., Biscoveanu, S., Islam, T., et al. 2022, *Phys. Rev. Lett.*, **128**, 191102
- Vennes, S., Nemeth, P., Kawka, A., et al. 2017, *Science*, **357**, 680
- Wenger, M., Ochsenbein, F., Egret, D., et al. 2000, *A&AS*, **143**, 9
- Wyszczkańska, R., Dybczyński, P. A., & Królikowska, M. 2020, *MNRAS*, **491**, 2119
- Yu, Q., & Tremaine, S. 2003, *ApJ*, **599**, 1129