

White dwarf plus FGK star binaries in *Gaia*

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Declaration

I declare that, unless otherwise stated, the work presented in this thesis is my own.

No part of this thesis has been accepted or is currently being submitted for any other qualification at the University of Sheffield or elsewhere.

The following chapters are based wholly or in part on previous publications:

- Chapter 3 (*Gaia* orbits for known Ultraviolet (UV) excess binaries): Garbutt et al. (2024)
- Chapter 4 (The *Gaia-Galaxy Evolution Explorer (GALEX)* UV Excess Sample for systems within 350 pc): Garbutt et al. 2026 (Submitted)

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Summary

White Dwarf (WD)s with an F, G or K type companion (or stars which evolved from such a companion) are the last common ancestor to a zoo of exotic phenomena. These systems can emerge from either a period of [Stable Mass Transfer \(SMT\)](#), or from a phase of [Common Envelope Evolution \(CEE\)](#).

We set about establishing a sample of such systems in [Chapter 3](#) ([Gaia orbits for known UV excess binaries](#)) using [Gaia Data Release \(DR\)3](#) data with previous [Ultra-violet \(UV\)](#) excess catalogues, finding a sample of 206 candidate [WD + FGK](#) systems, complete with orbital periods and a measure or estimation of the [WD](#) mass. We find that [WD + FGK](#) binaries can have a wide range of orbital periods. A large number of these systems are likely post-[SMT](#) systems based on their mass/period relationships, while others are difficult to explain either via [SMT](#) or standard [CEE](#).

We also work to construct a new [UV](#) excess sample from a [Gaia-Galaxy Evolution Explorer \(GALEX\)](#) crossmatch, compiling a sample of 2597 candidate [WD + FGK](#) binary systems within 350 pc in [Chapter 4](#) ([The Gaia-GALEX UV Excess Sample for systems within 350 pc](#)). We identify these systems by their [UV](#) excess as compared to what [MESA Isochrones & Stellar Tracks \(MIST\)](#) isochrones predict give the systems [Gaia DR3](#) stellar parameters, after applying corrections to systematic uncertainties found within the [UV](#) predictions of said [MIST](#) isochrones. We estimate the physical properties of the [WD](#) by fitting the excess [UV](#) flux to models, or through interpolation where there was only a clear excess in one [UV](#) band. We estimate the age of the system where possible by comparing against wide resolved [WD](#) companions, or by checking if the system is a known member of a cluster.

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Acronyms and Abbreviations

FUV Far Ultraviolet

NUV Near Ultraviolet

AGB Asymptotic Giant Branch

BD Brown Dwarf

BH Black Hole

CE Common Envelope

CEE Common Envelope Evolution

CMD Colour-Magnitude Diagram

CO Carbon-Oxygen

COS Cosmic Origins Spectrograph

CV Cataclysmic Variable

dM M Dwarf

DR Data Release

ESA European Space Agency

GALEX Galaxy Evolution Explorer

HB Horizontal Branch

HRD Hertzsprung-Russell Diagram

HST *Hubble Space Telescope*

IMF Initial Mass Function

IPD Image Parameter Determination

KH Kelvin-Helmholtz

LAMOST Large Sky Area Multi-Object Fiber Spectroscopic Telescope

LISA Laser Interferometer Space Antenna

LS Optically Luminous Star

MAMA Multi-Anode Microchannel Array

MCMC Markov Chain Monte Carlo

MIST MESA Isochrones & Stellar Tracks

MS Main Sequence

NS Neutron Star

ONe Oxygen-Neon

PEP Pauli Exclusion Principle

PN Planetary Nebula

RAVE RAdial Velocity Experiment

RG Red Giant

RGB Red Giant Branch

SED Spectral Energy Distribution

SMT Stable Mass Transfer

SNe Ia Type Ia Supernova/e

STIS Space Telescope Imaging Spectrograph

TGAS Tycho-*Gaia* Astrometric Solution

UV Ultraviolet

WD White Dwarf

ZAMS Zero-Age Main Sequence

Chapter 1

Introduction

“ And all the science, I don’t understand
it’s just my job five days a week ”

— Elton John, *Rocket Man*, 1972

1.1 Thesis outline

Throughout this thesis, I will present my work on cataloguing WD + FGK binaries. In the rest of Chapter 1 (Introduction), I will introduce the basic astronomical concepts relevant to this thesis, and in Chapter 2 (Methodology, Techniques and Instrumentation) I will delve more into the key methods used in my science chapters. In Chapter 3 (*Gaia* orbits for known UV excess binaries), I present my work taking previous samples of WD + FGK binaries, and finding orbits and binary parameters for these candidate systems, confirming the presence of three new WDs from this new collated set using *Hubble Space Telescope* (HST) spectroscopy and establishing a sample of 206 candidate WD + FGK binaries with orbital periods and WD mass estimates. Chapter 4 (The *Gaia-GALEX* UV Excess Sample for systems within 350 pc) presents a new sample of WD + FGK binary candidates that I found through investigating a Ultraviolet (UV) excess attributed to what optically appear to be single stars, based on a *Gaia-Galaxy Evolution Explorer* (GALEX) crossmatch. Finally, in Chapter 5 (Conclusion), I write a summary of my findings, address what my work has solved, what remains to be solved, and proposals for where to take my work going forward.

1.2 Stellar Evolution

It is believed that the majority of stars (≈ 97 per cent) form as intermediate to low mass $M_{\text{MS}} \lesssim 8\text{--}9 M_{\odot}$ stars that will go on to form WDs, and that many are found in multiple-star systems (Kepler et al., 2007; Holberg, 2009; Toonen et al., 2017; Cummings et al., 2018). Given that the fate of stars of $M_{\text{MS}} \lesssim 9 M_{\odot}$ is to become a WD, this means WD binaries should prove to be a common sight within the Galaxy. WDs can be found in binaries with many types of stars - from hot and heavy A type stars, Giants, tiny M Dwarf (dM)s and Brown Dwarf (BD)s, and even other degenerate objects such as other WDs, Neutron Star (NS)s and even Black Hole (BH)s. In this thesis, I focus on WDs in binary systems with an F, G or K type star (hereafter, WD + FGK). These systems are the last common ancestor to a host of exotic phenomena - ranging from double WD binaries, mergers, supersoft x-ray sources, Cataclysmic Variable (CV)s and, of course, Type Ia Supernova/e (SNe Ia) - and these systems can be formed from either a period of SMT, or by a phase of CEE. This is in contrast with WD + dM binaries, where those close enough to interact will all emerge as systems with short orbital period ($\lesssim 5$ d, Nebot Gómez-Morán et al. 2011) as the result of a phase of CEE, and will go on to become Cataclysmic Variable (CV)s - else they will remain detached systems if the periods are too long to bring them into contact within a Hubble time (≈ 14 Gyr). Before understanding the physics of how two stellar objects interact, it is useful to first understand how a star evolves in isolation.

1.2.1 Pre-MS

This first phase of stellar evolution begins before the MS, with protostars. These form in molecular clouds, where inhomogeneities cause localised clumps. These clumps collapse under their combined gravity, forming a dense core accreting matter - a pre-MS star. These stars are relatively cool (core temperatures of 100 - 1000s of K Dominik 2011), with

a large envelope of matter weakly bound to them (Silva Aguirre, 2018). The distribution of initial stellar masses across a star forming galaxy is known as the **Initial Mass Function (IMF)**, and many studies find that the characteristic mass (i.e. the most common initial mass formed) is below $0.1 M_{\odot}$ (Chabrier, 2003).

As the pre-**MS** evolves and accretes more matter, the core density increases as the core contracts, and the extended envelope slowly shrinks in towards the core, and the star evolves in a **Kelvin-Helmholtz (KH)** timescale,

$$\tau_{\text{KH}} \simeq \frac{GM^2}{2RL}, \quad (1.1)$$

where G is the gravitational constant, M is the mass of the star, R is the radius of the star, and L is the luminosity produced by the contraction of the star's core. The core eventually reaches a sufficient temperature and density for hydrogen fusion ($T \approx 13 \cdot 10^6 \text{ K}$, $\rho \approx 100 \text{ g/cm}^3$). As the outward radiative pressure of fusion counterbalances the inward further collapse of gravity, a true star is formed, and the star enters the **MS**.

1.2.2 Main Sequence (MS)

The defining feature of the **MS** is the burning of hydrogen into helium, maintaining hydrostatic equilibrium. Stars maintain relatively the same colour, luminosity and temperature throughout the **MS**. This is the longest active phase of a star's life, and around 90 per cent of its lifespan will be spent on the **MS** (Silva Aguirre, 2018). In the **MS**, evolution occurs on nuclear timescales,

$$\tau_{\text{nuc}} = \frac{\varepsilon q_{\text{nuc}} M c^2}{L}, \quad (1.2)$$

where ε is the amount of mass converted into radiative energy through nuclear burning (≈ 0.7 per cent), q_{nuc} is the fraction of mass involved in nuclear burning (≈ 10 per cent)

and c is the speed of light in a vacuum. For the Sun, this phase lasts $\sim 9 - 10$ Gyr.

An exception to the otherwise relative stability of the **MS** phase is stellar activity, which can cause luminosity to become variable. This activity occurs in the atmosphere of the stars, and is caused by magnetism - the reconnection of magnetic field lines causing flares, or starspots caused by magnetic fields blocking hot material from nearing the surface. This activity can be driven from the stars internal dynamo (the effects on activity weaken over time as the stars spin slows) or by being spun up by an external source, such as through binary interactions. This activity can see an increase in **UV** and X-ray flux as the temperatures in the corona and chromosphere get incredibly hot (coronal mass ejections in the sun, an example of such activity, have effective temperatures of 600 MK [Chen et al. 2025](#)).

Stars are given a spectral classification, known as a Morgan-Keenan classification ([Morgan & Keenan, 1973](#)), based on their effective temperature, T_{eff} , and thus also their colour. On the **MS**, the hottest, bluest and most luminous of these are O stars. As you go further down the spectral type classification (O, B, A, F, G, K, M) on the **MS**, these stars get cooler, less luminous and redder. Within each of these stellar types, we can further break down their classification as being ‘Early’ or ‘Late’ with numbers from 0-9, with lower numbers indicating ‘Earlier’, hotter stars within their stellar classification. Finally, a ‘luminosity class’ is appended in the form of a Roman numeral. I refers to super and hypergiants, with increasing numbers up to V for **MS** stars, with our own Sun being a G2V star. VI and VII are used to indicate subdwarfs and **WDs** respectively, though more commonly these are instead given the prefixes of sd or D.

Eventually, hydrogen fusion in the core stops, as the core has become depleted of hydrogen and only helium is left, with hydrogen surrounding the core in the envelope of the star. From here, the star moves off the **MS** and into a subgiant.

1.2.3 Post-MS

Past the [MS](#), evolution can vary depending on the mass of the star, with low mass stars ($M_{\text{MS}} \lesssim 2.5 M_{\odot}$, encompassing K, G, F and A stars) evolving slightly differently to intermediate mass stars ($2.5 < M_{\text{MS}} \lesssim 9 M_{\odot}$, encompassing mid to late [MS](#) B stars) which also evolve differently to higher mass stars ([Silva Aguirre, 2018](#)). Here, we will follow the evolution of a $1 M_{\odot}$ star as it evolves past the [MS](#), then afterwards discuss how things would change for more massive stars. How a $1 M_{\odot}$ star evolves across the [HRD](#) can be seen in [Figure 1.1](#).

As hydrogen is depleted in the core, the fusion of hydrogen instead occurs in a shell around the now helium-rich core. The outer envelope of the star is driven outwards as the core contracts in accordance with the mirror principle - that to maintain thermal equilibrium as the core contracts, the density and pressure of the envelope must decrease ([Pols, 2011a](#)), driving it outward, and the star thus cools as its surface area expands, becoming a subgiant. In the subgiant phase, evolution occurs at a rate set by the [KH](#) timescale ([Equation 1.1](#)). As the outer envelope cools, it becomes convective, and the star becomes a [Red Giant \(RG\)](#) star. For a star of $1 M_{\odot}$, the helium-rich core will grow as the hydrogen-burning shell continues to produce helium. The outer layers of the star cool, and convection can bring partially-processed fusion material to the surface of the star, known as a dredge-up.

As the star continues to evolve, the envelope continues expanding, making the star grow more luminous. As the star advances up the [RGB](#), it can lose mass through stellar winds since the envelope has now retreated so far from the core. The star will continue to evolve, slowly growing hotter and more luminous, until the conditions in the core are hot and dense enough for a helium flash ($T \approx 10^8 \text{ K}$, $\rho \approx 10^5 \text{ g/cm}^3$) and subsequently helium fusion. At this point, the outer envelope of the star shrinks far closer to the core, which expands (mirror principle as before) as can be seen in [Figure 1.2](#) - and the star

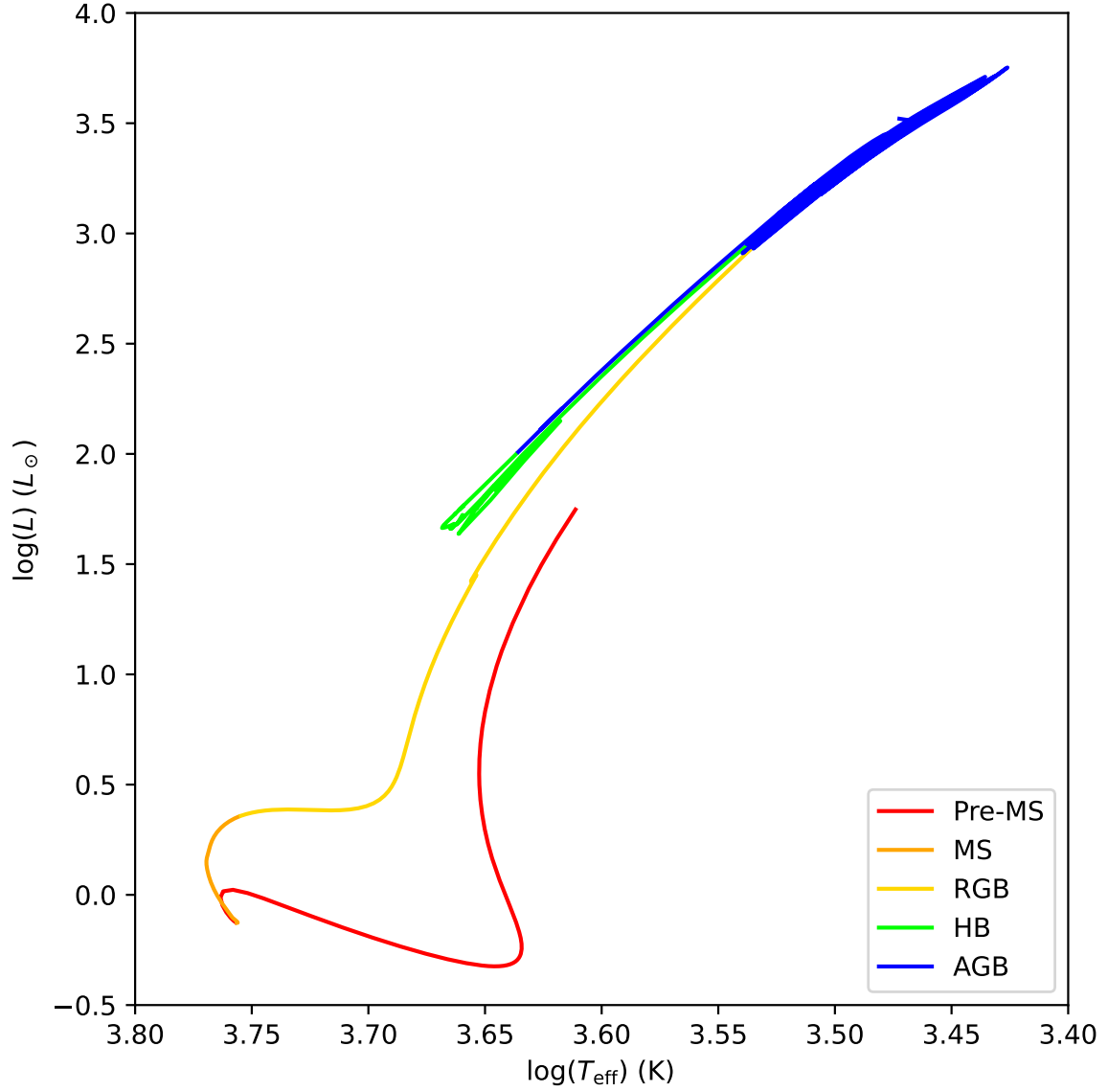


Figure 1.1: HRD showing the evolution of a $1 M_{\odot}$ star. Here, the pre-MS is shown in red, the MS in orange, the RGB in gold, the HB in green and the AGB in blue. There is overlap between the RGB, HB and AGB at the cooler, more luminous end of the domain. For clarity, the RGB leads onto the HB which then leads onto the AGB, which varies greatly both in respect to its luminosity L and its effective temperature, T_{eff} . Evolutionary models from Choi et al. (2016).

enters the **HB**, the second longest phase of its lifetime where it will steadily fuse helium into carbon, a little bit of nitrogen (mostly consumed in the process of forming oxygen), and oxygen in the core, whilst hydrogen fusion continues in a shell above the core.

Once helium in the core is depleted, helium burning occurs in a shell around the now **Carbon-Oxygen (CO)** core, with the hydrogen burning shell above that. The envelope again expands, and the star advances up the **AGB**. During this phase, mass is lost from the envelope owing to dust driven winds, and the radius of the star has grown substantially. Near the end of the **AGB**, the star begins to thermally pulse as the helium shell is depleted of fuel, and reignited as helium produced in the hydrogen shell makes its way downwards. As the outer envelope is lost, the hydrogen shell has increasingly less fuel to burn, until finally it runs out - the envelope is ejected and the **CO** core is left as a post-**AGB** star, which rapidly shrinks and heats up, and can ionise the ejected envelope as a **Planetary Nebula (PN)**, leaving the inert core behind as a **WD** (Engels, 2005).

More massive stars evolve slightly differently. For stars more massive than $\approx 2.5 M_{\odot}$, the evolution from the end of the **MS** can be far quicker a 3 msol star has a lifespan of ≈ 370 Myr, whilst a 1 msol has a lifespan of ≈ 10 Gyr (Strobel 2020), with the increased mass leading to a far more rapid evolution through the **RGB** as the conditions for helium burning in the core can be met much more readily, with no need for the helium flash as the core isn't degenerate at the end of the **RGB**. Past the **RGB**, stars up to $\approx 8 - 9 M_{\odot}$ will follow a similar evolutionary track as described for the $1 M_{\odot}$ case described above, though with shorter timescales. For stars above this mass, their cores can go on to burn carbon, neon, oxygen and potentially silicon, each with shorter and shorter timescales (for an extreme example, a $25 M_{\odot}$ star will spend 7 Myr burning hydrogen, and 1 d burning silicon Bolte 2004), building up more and more shells above the core, with each burning lighter elements than those beneath them. The limit of this nuclear synthesis is iron - at which point fusion becomes inefficient. If the mass of the core exceeds the

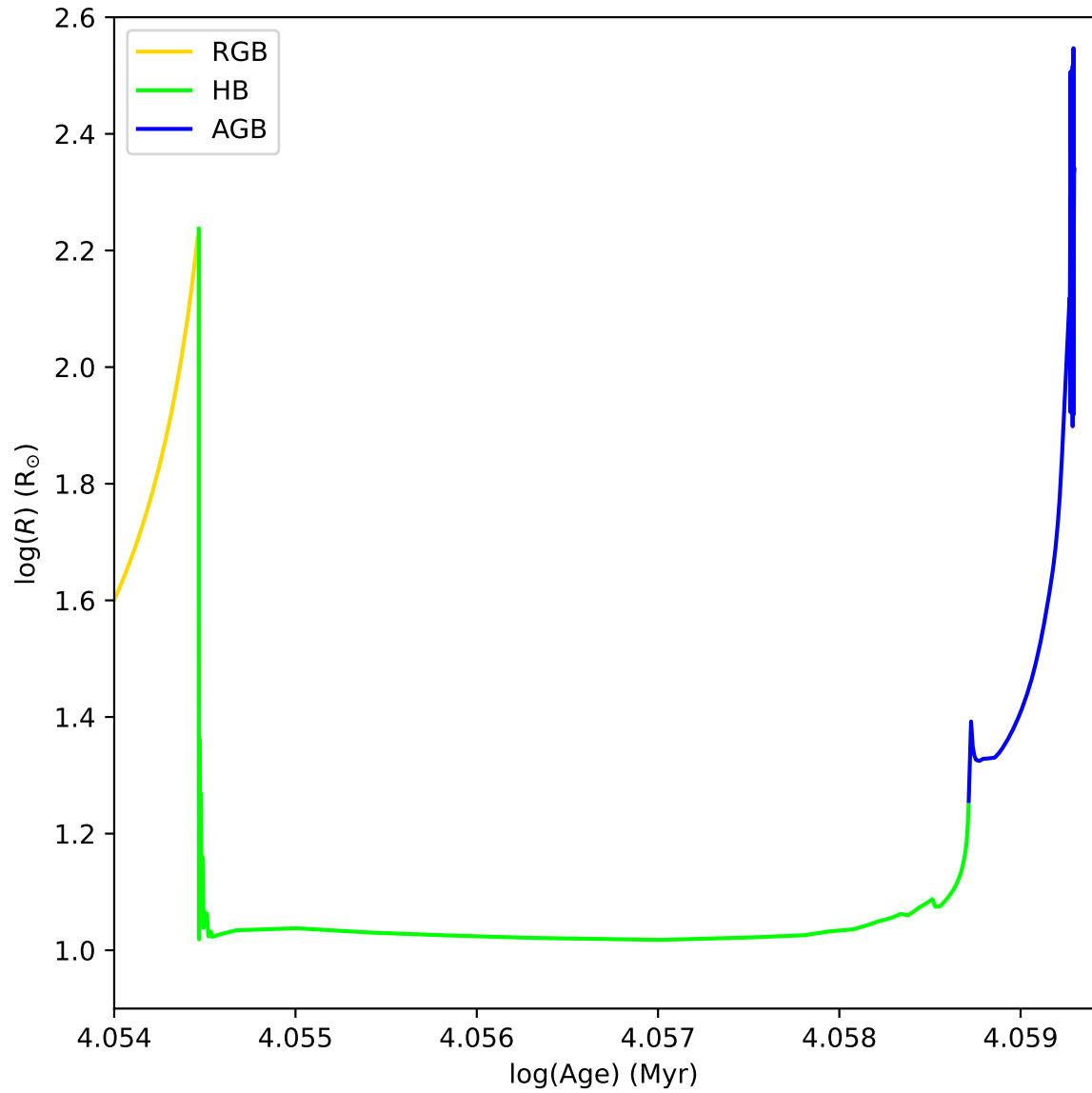


Figure 1.2: The relationship between age and radius R for across the end of the RGB, the HB and the AGB. As can be seen, the radius significantly decreases onto the HB compared to the two giant phases either side of it. Evolutionary models from from Choi et al. (2016).

Chandrasekhar limit ($\approx 1.44 M_{\odot}$), electron degeneracy pressure is overcome and the core collapses into either a **NS**, or a **BH** if even neutron degeneracy pressure is inefficient to stop the collapse.

Stars with a mass lower than $\approx 0.5 M_{\odot}$ likewise evolve differently. These stars won't be able to fuse helium, and so will not become **RG** stars, instead transitioning directly into **WDs**. This process takes a very long time, and the age of the universe isn't old enough for stars below $\approx 0.7 M_{\odot}$ to have evolved into **WDs** yet. Such **WDs** would be extremely low mass, and we should not expect to see any of these in the Galaxy - yet, unexpectedly, we do.

1.2.4 White Dwarf (WD)s

Once a star has become a **WD**, it is dead. It no longer fuses elements - a dead core floating through space held together by electron degeneracy. Electron degeneracy arises thanks to the **Pauli Exclusion Principle (PEP)** - that no two fermions (in this scenario, electrons) can exist in the same quantum state at the same time. This counteracts the gravity trying to collapse the core of the **WD** any further. Indeed, it is because of the **PEP** that more massive **WDs** have the smaller radii - requiring a higher electron degeneracy pressure (in turn requiring higher densities) in order to counterbalance the increased gravitational forces that comes with the increasing mass.

WDs consist of their degenerate core and an atmosphere. The lowest mass lone **WD** progenitors, those which never burned helium in their cores (i.e. those which will form from **dM** stars - though none are old enough to reach this stage yet), will have a core formed of degenerate helium, whilst those which reached the **AGB** will have cores of primarily carbon and oxygen. The very highest mass **WDs** may have neon and magnesium in their cores as a result of carbon burning, if their progenitor star was able to fuse magnesium into neon - though these cases are much rarer. Owing to the great

Table 1.1: The different spectral types of WDs and their flags, as initially proposed by Sion et al. (1983).

Spectral Classification	Definition
DA	Strong HI lines in the atmosphere
DB	Strong HeI lines in the atmosphere
DO	Strong HeII lines in the atmosphere
DQ	C lines present in the atmosphere
DZ	Metal lines present in the atmosphere
DC	No particularly strong lines in the spectrum of the atmosphere
DX	Unclear spectrum

densities of WDs (their surface gravity, $\log(g)$, is typically $\approx 8 \text{ cm} / \text{s}^2$), heavier elements sink to the centre of the core.

Atop the core and thin envelope, the WD has a thin atmosphere composed of the remnants of its envelope. Given these atmospheres are what we see of the WD, we use these to classify them by identifying key spectral lines. These classifications - DA, DB, DO, DQ, DZ, DC and DX - were initially suggested by (Sion et al., 1983), and the definition of each is outlined in Table 1.1.

Given that WDs no longer fuse elements, they are no longer generating energy - they start off very hot ($\lesssim 90 \text{ kK}$), but cool relatively quickly, as shown in Figure 1.3. Owing to these extreme temperatures, WDs dominate at much bluer wavelengths, peaking in the UV. As a WD cools over time, the carbon and oxygen in the core crystallise, which slows the cooling process (Tremblay et al., 2019). There is, however, a quirk with ultramassive ($M \gtrsim 1.05 M_{\odot}$) WDs - an observed excess of such systems occupying a consistent part of the optical CMD - the Q branch (Cheng et al., 2019; Tremblay et al., 2019; Camisassa et al., 2021). This is believed to be caused by neon sedimentation causing a release of gravitational energy, further slowing the cooling of these systems, which otherwise cool primarily through thermal radiation and to a lesser extent through neutrino emission.

WDs range in mass depending on the mass of the core of their progenitor. There is an upper limit to this, $\approx 1.44 M_{\odot}$, the Chandrasekhar limit. Beyond this mass, the PEP

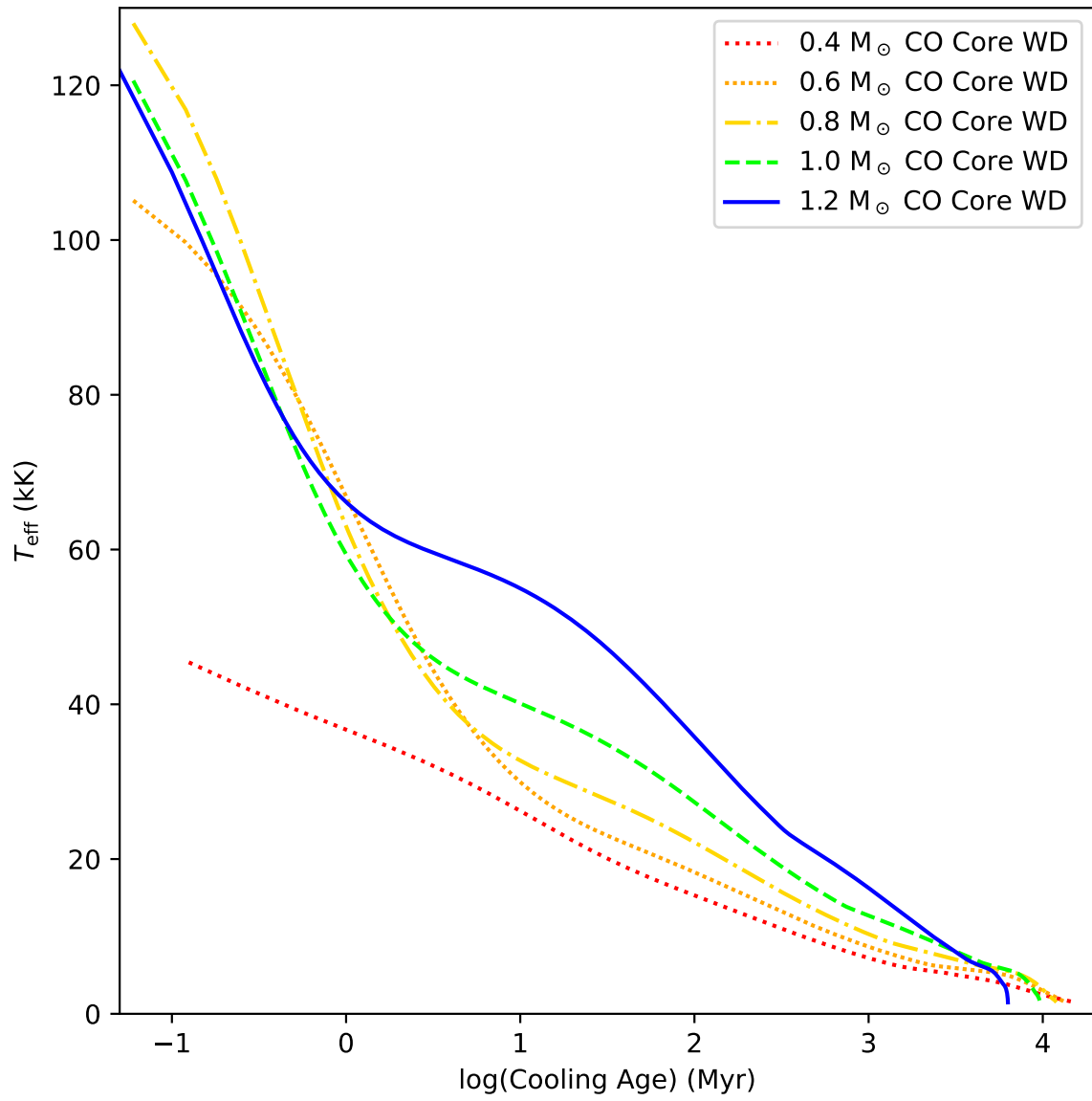


Figure 1.3: Cooling tracks for a 0.4, 0.6, 0.8, 1.0 and 1.2 $M_{\odot}$ WD, using the evolutionary models of Bédard et al. (2020).

with electron degeneracy can no longer hold the core together, and stars with a core above this mass will collapse into a [NS](#) if neutron degeneracy can hold the core together, or into a [BH](#) if even neutron degeneracy is insufficient. There *should* also be a lower limit on the mass of [WDs](#) that we can observe - recall Section [1.2.3](#) - the universe isn't old enough to produce [WDs](#) below $\approx 0.45 M_{\odot}$ (see e.g. [Marsh et al. 1995](#)) - yet we find some as low as $0.17 M_{\odot}$. These come about not through isolated stellar evolution alone - but through binary interactions.

1.3 Binary Evolution

Many stars do not form in isolation, but rather in multiple-star systems - with the general trend suggesting that more massive stars have higher binarity compared to lower mass stars (Offner et al., 2023). Systems with an F, G or K type primary have a binarity rate of ≈ 50 per cent, increasing for A and B type primaries up to around ≈ 90 per cent for O type stars. Given we expect WDs to form from mid-B to K type stars, this would suggest that we should expect many WDs to be found in multiple star systems, and that we might expect many systems containing a mid-B to K primary with a MS companion to, later in it's evolution, to form a WD + FGK binary.

The most critical part of binary interactions is the transfer of mass between the two stars. This occurs as the envelope of one of the stars expands (most commonly as it advances onto the RGB or AGB), leading it into overfilling its Roche lobe - the limit at which material is gravitationally bound to the star in a binary system, as can be seen in Figure 1.4. A star will begin to lose mass should it overfill its Roche lobe, and its companion can accrete some of this mass.

1.3.1 Common Envelope Evolution (CEE)

If two stars are close enough (i.e. with an orbital period, $P_{\text{orb}} \lesssim 10^4 \text{ d}$), when the more massive star ages and enters its RGB or AGB phase (or less commonly during the Hertzsprung gap), its companion can be swallowed by the envelope of the giant star - a Common Envelope (CE) surrounds both stars (Paczynski, 1976). Here, the envelope has greatly exceeded the Roche radii of both stars and the mass transfer is greatly unstable and non-conservative (Paczynski & Ziółkowski, 1967; Tout, 2012). The companion cannot accrete all the matter as the accretion rate is too high (De Marco et al., 2011). In most cases, this causes the two stars to spiral in as drag causes orbital energy to be transferred to the CE. It is challenging to reproduce the complex hydrodynamics

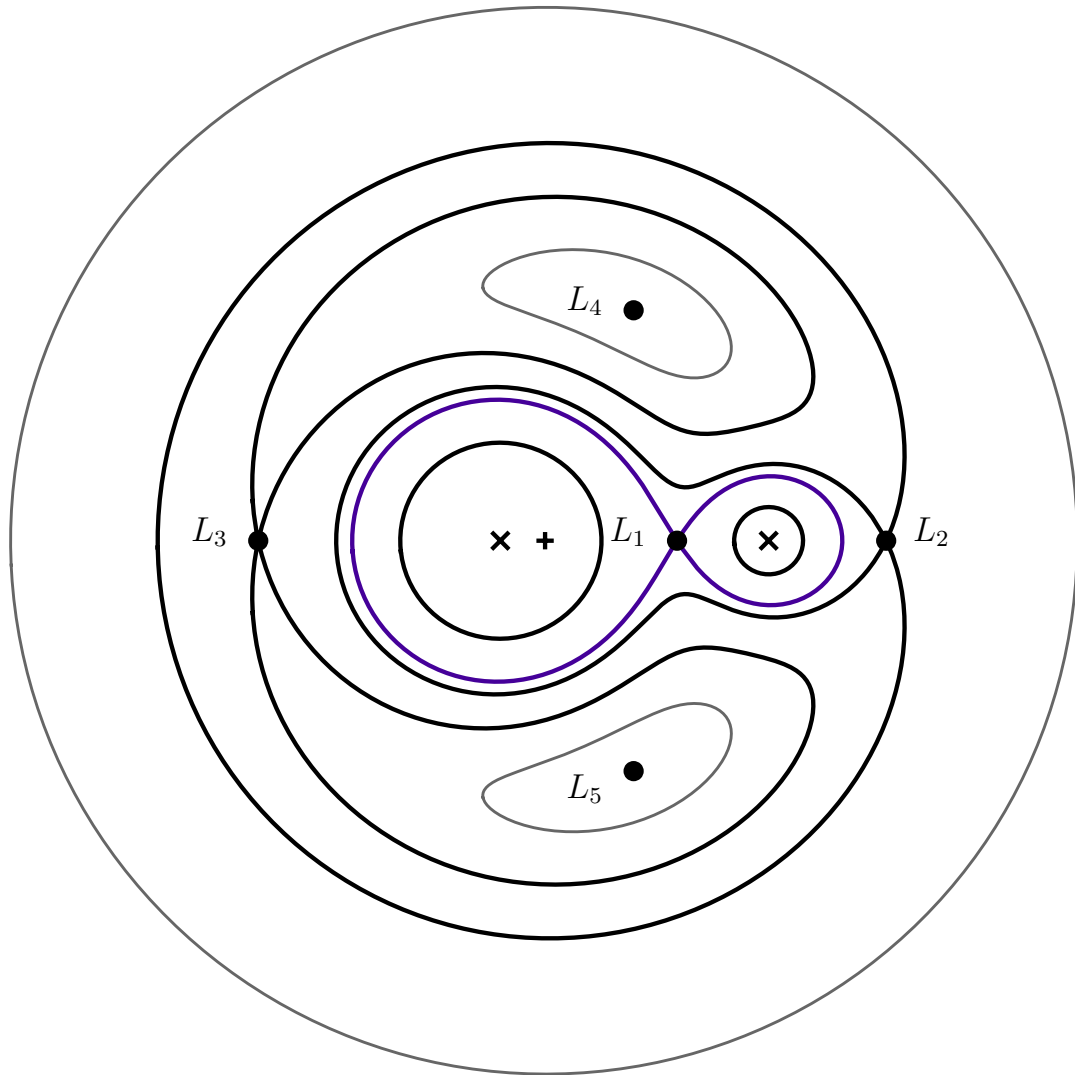


Figure 1.4: Roche potential diagram where the system has a mass ratio of 0.2, adapted from [Brown \(2023\)](#). The Lagrangian points (where there is gravitational equilibrium) are labelled as $L_1 - L_5$, with the purple contour indicating the Roche lobes of the two stars, with the crosses indicating the centres of each star and the plus indicating the centre of mass.

involved in the CE through hydrodynamical simulations (Passy et al., 2012; Ohlmann et al., 2016; Ondratschek et al., 2022; Moreno et al., 2022), and instead we often use a simplification - using the α formalism to parametrise the fraction of lost orbital energy that is transferred into the envelope to unbind it (Tutukov & Yungelson, 1979; Iben & Tutukov, 1984; Webbink, 1984, 2008; Zorotovic et al., 2010; De Marco et al., 2011).

The α formalism is built upon the work of Tutukov & Yungelson (1979), with Webbink (2008) defining the formalism as

$$\alpha_{\text{CE}} \equiv \frac{E_e}{(E_{\text{orb}}^{(\text{f})} - E_{\text{orb}}^{(\text{i})})}, \quad (1.3)$$

where α_{CE} is the CE efficiency, E_e is the envelope energy, $E_{\text{orb}}^{(\text{f})}$ is the final orbital energy and $E_{\text{orb}}^{(\text{i})}$ is the initial orbital energy. These are each defined by

$$E_e = -\frac{GM_1 M_{1e}}{\lambda R_{1,L}}, \quad (1.4)$$

$$E_{\text{orb}}^{(\text{f})} = -\frac{GM_2 M_{1c}}{2A_f}, \quad (1.5)$$

$$E_{\text{orb}}^{(\text{i})} = -\frac{GM_1 M_2}{2A_i}, \quad (1.6)$$

where M_1 is the mass of the primary (i.e. the star whose envelope is surrounding its own core along with the companion star), M_{1e} is the mass of envelope of the primary, λ is a binding energy parameter approximated by 1D models (see e.g. Xu & Li 2010), $R_{1,L}$ is the Roche-lobe radius of the primary star at the beginning of mass transfer, $M_{1,c}$ is the mass of the core of the primary, M_2 is the mass of the secondary, A_f is the final orbital separation and A_i is the initial orbital separation.

Zorotovic et al. (2010), from studying WD + dM binaries, finds $\alpha_{\text{CE}} \approx 1/3$ - though this value may not be universal for all types of star or evolutionary phase. A value of $\approx 1/3$ seems to hold well for double WD binaries (Scherbak & Fuller, 2023) and for

WD + BD binaries (Zorotovic & Schreiber, 2022), though it is less sure for WD + AFGK binaries. Parsons et al. (2015) find a lower value of $\alpha_{\text{CE}} \approx 0.05 - 0.2$ to be more likely for the short-period (~ 0.5 d) WD + F binary TYC 6760-497-1, whilst Yamaguchi et al. (2024b) find that a high efficiency $\alpha_{\text{CE}} \gtrsim 0.6$ is required to form long period ($P_{\text{orb}} \gtrsim 10^2$ d) high mass WD binaries - though Belloni et al. (2024) find that the more standard $\alpha_{\text{CE}} \approx 1/3$ can produce such systems if the WD progenitor is at the tip of the thermally pulsing AGB phase - allowing the star to have lost a great deal of mass and weakening how strongly bound the envelope is. Broadly, the α formalism works well for short period systems (e.g. WD + dM systems, and some WD + FGK systems), though longer period systems (such as wider WD + FGK binaries) are a challenge for α formalism.

1.3.2 Stable Mass Transfer (SMT)

Another way of producing these longer period systems is through a period of SMT. This channel of binary evolution, as proposed by Webbink (2008) for WD + MS progenitor systems, is thought to occur if both stars have similar masses, or else as the two components come into contact as the initially more massive star (hereafter, the donor star) leaves the MS before its outer envelope is significantly expanded and becomes convective, where the star would be unable to adjust its radius and thus leading to unstable mass transfer and a CE. In this scenario, the initially less massive companion (hereafter, the accretor) steadily accretes mass lost from the donor star as it steadily overfills its Roche lobe, as described in Figure 1.4, which can lead to a widening of the binary through tidal forces, should the mass of the accretor overtake the mass of the donor, as described by

$$\frac{\dot{a}}{a} = 2\dot{M}_{\text{d}} \frac{M_{\text{d}} - M_{\text{a}}}{M_{\text{d}}M_{\text{a}}}, \quad (1.7)$$

where a is the semi-major axis of the system, M_d and M_a are the donor and accretor masses respectively, with $\dot{a}$ and $\dot{M}_d$ being the changes of these properties with respect to time (Carroll & Ostlie, 2014; Pols, 2011b). This is assuming that the process is fully conservative (i.e. no mass or angular momentum is lost by the binary, and is perfectly transferred), which may not be the case - these systems could be fully, partially or completely non-conservative. Podsiadlowski (2014) claims the transfer is quasi-conservative, with a small amount of mass and angular momentum being unbound from the system.

To take into account lost mass and momentum, we can consider two additional factors; β to represent the fraction of mass successfully accreted by the accretor, and γ to represent the ratio of the mass loss to angular momentum(J) loss, i.e.

$$\gamma = \frac{\dot{J}M_{\text{Tot}}}{\dot{M}J_{\text{init}}}, \quad (1.8)$$

where J_{init} is the initial angular momentum of the system, M_{Tot} is the total mass of the system (Paczynski & Ziolkowski, 1967; Nelemans et al., 2000). Applying these factors, the equation describing the change in separation instead becomes

$$\frac{\dot{a}}{a} = -2\frac{\dot{M}_d}{M_d} \left(1 - \beta \frac{M_d}{M_a} - (1 - \beta)(\gamma + 0.5) \frac{M_d}{M_d + M_a} \right), \quad (1.9)$$

which is more complex, as both β and γ are non-trivial and depend on factors such as the masses of the stars and how mass is transferred (wind accretion and accretion by a circumbinary ring will have vastly different values of γ for instance (Pols, 2011b)) This can lead to a wide range of possible outcomes, though the most likely result is that of a very low mass WD as SMT occurs on (or occasionally just before) the RGB, making it unlikely that this channel will produce CO core WDs - as these stars will not have undergone helium burning.

1.3.3 Eccentric Mass Transfer

Although tidal forces generally work to circularise orbits, binary systems can still have eccentric orbits at the onset of mass transfer (Davis et al., 2013). This can complicate matters, as the separation between the two stars changes, thus changing their Roche radii, with mass transfer being most effective at periastron and least effective at apastron. Parkosidis et al. (2026a,b) investigate how eccentricity affects the outcome of mass transfer, assuming both conservative (Parkosidis et al., 2026a) and non-conservative (Parkosidis et al., 2026b) scenarios.

Parkosidis et al. (2026a) find that, assuming stable and conservative mass transfer through Roche lobe overflow, their models can produce wide eccentric binaries, which are in agreement with many observed systems (e.g. Yamaguchi et al. 2024a). Parkosidis et al. (2026b) then considers the stable, non-conservative scenario, and investigated how different methods of mass loss affect both the eccentricity and orbital separation of these systems for given mass ratios - and find that these two factors are intrinsically linked - wider separations being more eccentric, and closer separations being more circular. They find that wind accretion widens and increases the eccentricity of the system, isotropic re-emission (where winds or jets from the accretor drive out incumbent mass) likewise widens and increases eccentricity if the mass ratio is less than 1.28, but shrinks it otherwise. They find that mass loss through L_2 (see Figure 1.4) is the most efficient method of extracting angular momentum from the system, with a mass ratio of less than 0.3 and an eccentricity of at least 0.2 widening the binary, with this method of mass loss causing the orbit to shrink should the mass ratio be greater.

1.3.4 Exotic End Products

WD + FGK binaries can go on to form a host of exotic systems, depending on the orbital period of the system, as can be seen in Figure 1.5 - from double WD systems, mergers,

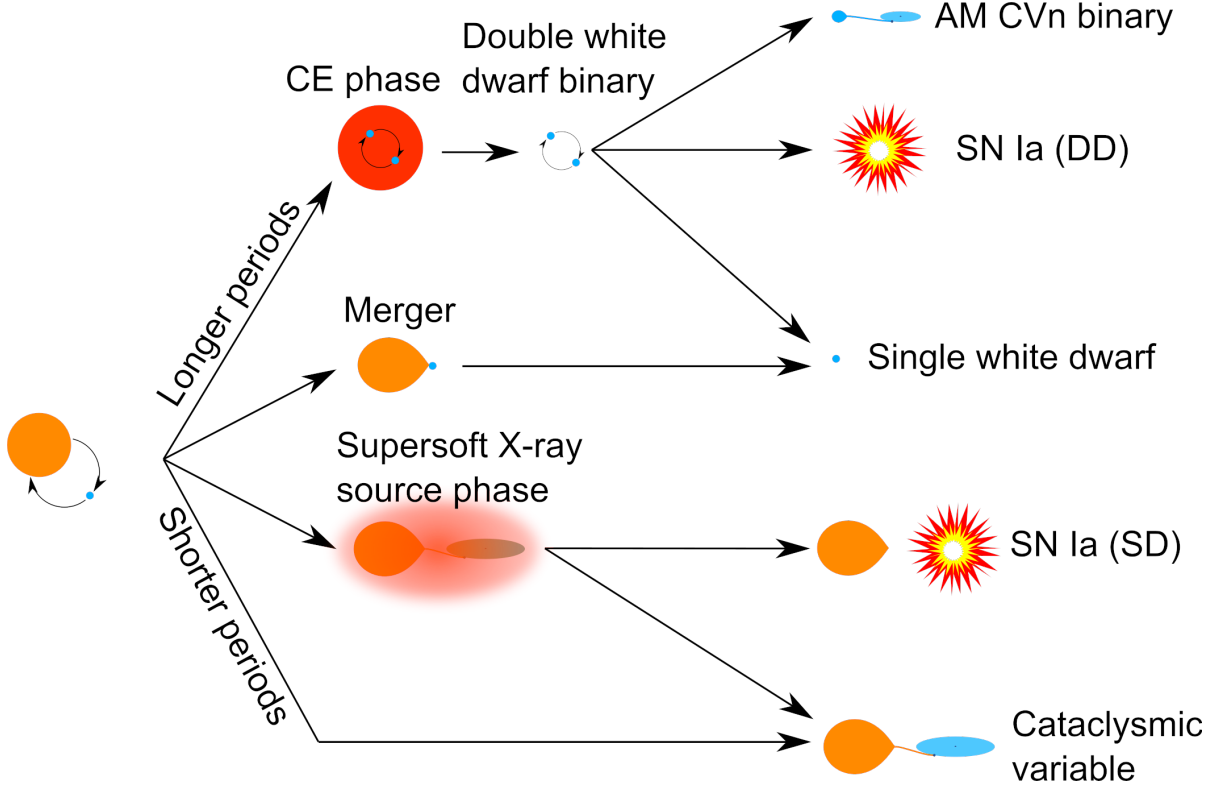


Figure 1.5: The evolutionary pathways stemming from post-interaction WD + FGK binaries, adapted from Parsons (2023). The end products vary depending on the period of the system post-interaction, and can go onto become a zoo of exotic astronomical phenomena.

supersoft x-ray sources into Type Ia Supernova/e (SNe Ia) and CVs.

Double WD Binaries

When the companion of the WD evolves, the system may undergo a second phase of CEE as the envelope of the companion engulfs the WD (it could also undergo another phase of SMT, as discussed more in the upcoming section regarding SNe Ia). As with before (see Section 1.3.1), this causes the two systems to spiral in, robbing the system of angular momentum and, if both stars survive, they will become a double WD binary.

Double WD binaries are interesting and important systems. They are the most abundant source of gravitational waves within our Galaxy (Finch et al., 2023), which will cause them to be a source of foreground noise for detectors such as Laser Interferometer

Space Antenna (LISA) (Amaro-Seoane et al., 2017) and they will need to be understood and mapped to best use LISA to find other sources of gravitational waves. Double WDs are themselves a precursor system to other phenomena, including AM CVn type binaries, SNe Ia (See later subsection on SNe Ia) and merging into a single, more massive WD.

AM CVn binaries can occur when Roche lobe overflow occurs in a double WD binary, where the larger, less massive WD loses mass to its more massive partner (Nelemans et al., 2004; Ramsay et al., 2018). Such systems will have incredibly short orbital periods, of $\lesssim 1$ h, and are likely to themselves merge (Marsh et al., 2004; Shen, 2015).

Mergers

Mergers are, as the name suggests, the result of two stellar objects (stellar cores or degenerate objects) coalescing into one object. There are three main points in the evolution of a WD + FGK binary where this merger can happen; when the FGK star evolves and the system undergoes a CE phase, as a double WD binary, or after a phase of being an AM CVn type binary. In the first of these three, the mass of the merger product is approximately equal to the sum of the WD mass and that of the stellar core, as the process is relatively conservative (Temink et al., 2020). The merger product here can be a giant star, a WD or even a SNe Ia (Izzard et al., 2007; Zhang & Jeffery, 2013; Zhang et al., 2020; Temink et al., 2020).

Double WD mergers (regardless of if the binary was ever an AM CVn type binary) have different evolutionary outcomes. Shen et al. (2012) proposes that the outcomes of a double WD merger range from a higher mass Oxygen-Neon (ONe) WD or if the mass of the product is above the Chandrasekhar mass, a NS will likely emerge, opposed to a SNe Ia. This comes about as the increased mass from accretion causes carbon ignition, with the resultant flash converting the accreted CO into ONe, with recurrences actually cooling the core of the WD owing to emission of neutrinos. As the core density increases, it overcomes electron degeneracy and collapses into a NS, with the resultant

shock ejecting accreting material (Saio & Nomoto, 1985). Dan et al. (2014) investigates several outcomes depending on the individual masses of the WD components - with several channels for different detonations on the surface of the more massive WD (such as helium detonations, which the WD should survive unless it also triggers a carbon detonation in a dynamically driven double degenerate double detonation - see e.g. Guillochon et al. 2010; Sato et al. 2015; Shen et al. 2018), massive CO core WDs, SNe Ia, and core-collapse supernovae leaving behind a NS.

Webbink (1984) also proposes scenarios for the mergers of He + He core WDs, CO + He core WDs and CO + CO WDs. In the case of double He core WDs, if the merger product is sufficiently massive ($\gtrsim 0.5 M_{\odot}$), then it can ignite and begin burning helium - becoming a hot subdwarf (Webbink, 1984; Hall & Jeffery, 2016). In regards to the CO + He core merger scenario, ignition of accreted helium occurs on the CO core WD, and a helium burning shell surrounds the CO core component. A CE surrounds the system, which the He core WD does not survive. This helium envelope surrounding a CO core is a R Coronae Borealis type star (Webbink, 1984; Clayton, 1996, 2012). The CO + CO scenario has a ignition of CO fusion in the envelope of the more massive WD, with Webbink (1984) confident that this will result in a SNe Ia - though as previously discussed, this may not be the case.

Type Ia Supernova/e (SNe Ia)

SNe Ia are the most dramatic end product of a WD + FGK binary system - a thermonuclear explosion that destroys a WD. SNe Ia have characteristic spectra and light curves, which make them relatively easy to identify, and their light curves are standardisable making them useful cosmologically as standardisable candles. Broadly, SNe Ia are defined by their complete lack of hydrogen in their spectra, and strong silicon lines in their spectra at the time of maximum luminosity (Wheeler & Harkness, 1990). The early spectra of SNe Ia are dominated primarily by elements from oxygen to calcium, with

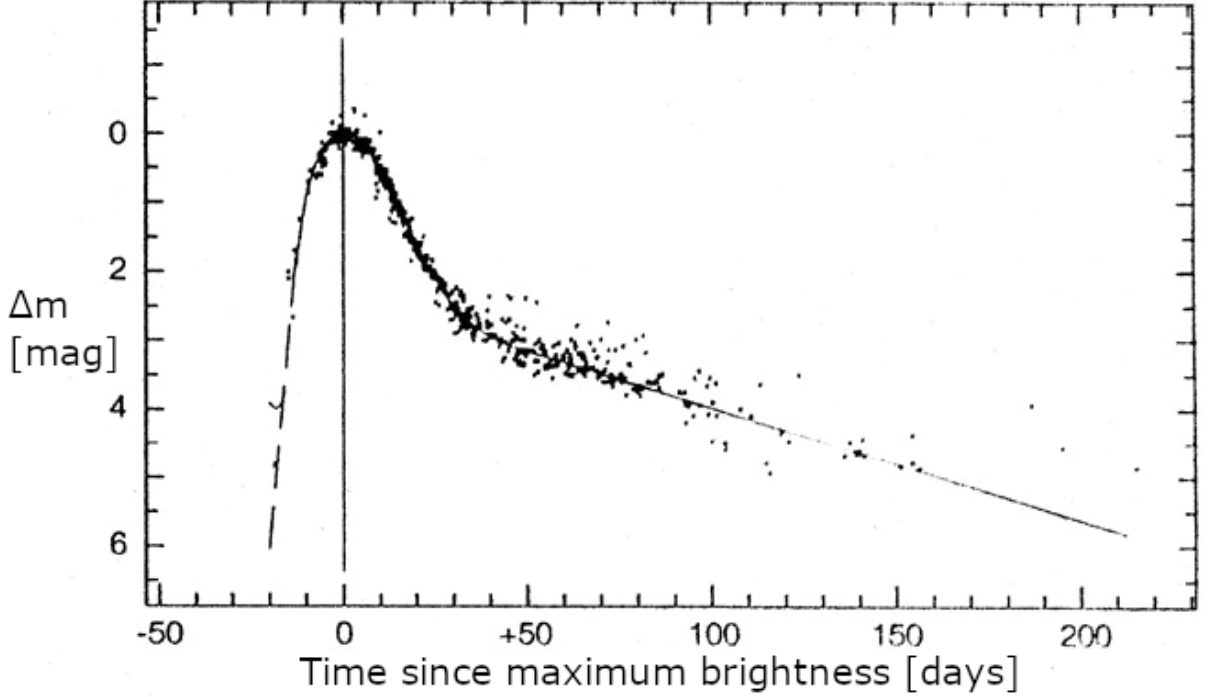


Figure 1.6: Standard B light curve of SNe Ia, based on 22 SNe Ia. Adapted from Cadonau (1987); Branch & Tammann (1992).

peaks shifting to neutral iron then ionised iron as time advances from peak luminosity (Branch & Tammann, 1992; Filippenko, 1997; Hillebrandt & Niemeyer, 2000). The light curves of SNe Ia rise rapidly towards peak luminosity, before decaying exponentially (Nomoto, 1982), as can be seen in Figure 1.6. These light curves are standardisable by comparing their peak brightness with the rate of evolution of the supernovae brightness (Rust, 1974; Pskovskii, 1977, 1984; Phillips, 1993), making them useful for constraining distances.

There are two pathways to SNe Ia - the single degenerate pathway, and the double degenerate pathway. In the case of the former, this involves a WD accreting matter from a non-degenerate companion - a MS or more likely a giant star - by Roche lobe overflow (Whelan & Iben, 1973) in what is referred to as a supersoft x-ray source phase (Gänsicke et al., 2000; Parsons et al., 2015; Bhattacharya, 2017). In this pathway, the WD steadily accretes hydrogen from its companion, and a shell of hydrogen burning

begins on the surface of the WD. This helium layer will detonate as the WD approaches the Chandrasekhar limit, as the increased mass leads to the WD getting increasingly hotter and the helium layer (resultant from the hydrogen burning) detonates, causing the WD to destabilise and explode (see e.g. Nomoto 1982 for the physics of the detonation disrupting the WD). It should be noted that a supersoft x-ray source phase does not always lead to a SNe Ia - with some systems going on instead to become CVs.

The double degenerate channel involves instead two WDs. There are a few proposals for how this channel works (Livio & Mazzali, 2018; Rebassa-Mansergas et al., 2019). The first proposals of this method, by Webbink (1984); Iben & Tutukov (1984), have the more massive WD accrete material from its less massive companion, which has overflowed its Roche lobe, such as in an CM CVn type binary. A SNe Ia can also occur as the result of a merger between the two WD components, should they both be of relatively high mass ($\gtrsim 0.7$) $M_{\odot}$ (Pakmor et al., 2012; Sato et al., 2015). Here, compressed heating causes carbon ignition which disrupts the primary WD causing it to detonate as a SNe Ia. The secondary companion of the WD can survive the SNe Ia in both the single and double degenerate channels (Pan et al., 2010, 2012a,b; Burmester et al., 2023; Ferrario, 2025).

Generally, observations prefer the double degenerate model (see e.g. Howell et al. 2006; Hicken et al. 2007; Yoon et al. 2007; Scalzo et al. 2010; Chen et al. 2012; Horesh et al. 2012; Liu et al. 2012; Graham et al. 2015), though there is evidence that multiple channels can lead to SNe Ia, such as the bimodality of spectral features (Benetti et al., 2005), circumstellar material (Dilday et al., 2012), the ejected mass-nickel relation (Scalzo et al., 2014) and stable iron peak-element nucleosynthesis (Seitenzahl et al., 2013; Yamaguchi et al., 2015).

Cataclysmic Variable (CV)s

CVs are the final stage of close WD + dM binaries, and are also an end channel for the closest WD + FGK binaries. In these systems, the WD accretes matter from its

companion (in this case, a **MS** star, though **dMs**, **Brown Dwarf (BD)**s and giants are also viable) via an accretion disk (Warner, 1995; Littlefair et al., 2008; Rebassa-Mansergas et al., 2021; Pala et al., 2022). **WD** + **FGK** stars can also form **CV**s after a phase of being a supersoft xray source (see e.g. Parsons et al. 2015; Hernandez et al. 2020). As the **WD** accretes matter, it will periodically undergo classical novae as matter (both accreted and core material) is ejected owing to explosions caused by the ignition of the accreted material - occurring owing to the high densities of the accreted material, and the high temperatures of the **WD** (Gehrz et al., 1998; Yaron et al., 2005; Epelstain et al., 2007). There are a few end-stages for **CV**s; (1) the secondary could diminish itself into a planetoid as it loses mass to the **WD** - leaving the **WD** to appear mostly isolated, (2) the system could evolve into an **AM CVn** type binary as the **MS** evolves (see the earlier section on double **WD** binaries), or the system could erupt as a **SNe Ia** (Warner, 1995).

Chapter 2

Methodology, Techniques and Instrumentation

“ And pray that there’s intelligent
life somewhere out in space
'Cause there’s bugger all down here on Earth ”

— Monty Python, *The Galaxy Song*, 1989

Introduction

In this chapter, I outline some more specific methods used in [Chapter 3](#) (*Gaia* orbits for known UV excess binaries) and [Chapter 4](#) (The *Gaia-GALEX* UV Excess Sample for systems within 350 pc). I start out with a general introduction to the *Gaia* mission and what we use from *Gaia* DR3. I then go on to discuss binary detection classifications and methods, before finally discussing model fitting.

2.1 *Gaia*

The *Gaia* spacecraft is a space telescope operated by the [European Space Agency \(ESA\)](#) ([Gaia Collaboration et al., 2016a](#)). Launched on 2013/12/19, the telescope ceased operations on 2025/03/27, though data is still being processed, with DR3 being the most recent at the time of writing. DR4 is scheduled for release 2026/12/02 and DR5 not expected until the end of 2030 at the earliest.

Gaia DR1 ([Gaia Collaboration et al., 2016b](#)) was released 2016/09/14. DR1 provided m_G band magnitudes and sky positions for its sources. For sources in common with the Tycho-2 catalogue, proper motion is also given ([Michalik et al., 2015](#)). *Gaia* DR2 ([Gaia Collaboration et al., 2018](#)) (released 2018/04/25) expanded on this greatly, providing sky positions and proper motion for more than 1.3 billion sources, with m_G band values limits at 21 mag and 3 mag at the dimmest and brightest ends respectively.

Gaia DR3 ([Gaia Collaboration et al., 2023a](#)) is the most recent of the *Gaia* releases. In addition to providing photometric and astrometric parameters to over 1.4 billion sources, it also provides various new parameters and related catalogues. Of particular importance to the works in this thesis are the estimates on stellar parameters ([Creevey et al., 2023](#)) (used prominently in [Chapter 4](#) (The *Gaia-GALEX* UV Excess Sample for systems within 350 pc)) and catalogues of stellar multiplicity [Gaia Collaboration et al.](#)

(2023c) (used prominently in Chapter 3 (*Gaia* orbits for known UV excess binaries)).

The stellar multiplicity catalogue, Gaia Collaboration et al. (2023c) gives several useful parameters for determining properties of the binaries. The `nss_two_body_orbit` catalogue directly gives a measure of the orbital period (P_{Orb}) and eccentricity (e) for all given binary classifications, as given by the `nss_solution_type` column (this serves as a flag as to which of their models best fits the observations), though inclination (i) is only given for eclipsing systems, and centre of mass velocities and semi amplitudes (the maximum velocities of the stars, K) are only given for spectroscopic systems. Some of these parameters can however be determined for astrometric systems, as the `nss_two_body_orbit` catalogue contains the Thiele-Innes parameters - A , B , F and G , which are measured elliptical coordinates that encode the photocentric semi-major axis (a_0), i , the argument of periapsis (Ω), and the periastron longitude (ω), which can be converted into these parameters using the NSS TOOLS python package¹ (Halbwachs et al., 2022). These parameters are defined as

$$A = a_0 [\cos(\omega) \cos(\Omega) - \sin(\omega) \sin(\Omega) \cos(i)], \quad (2.1)$$

$$B = a_0 [\cos(\omega) \sin(\Omega) + \sin(\omega) \cos(\Omega) \cos(i)], \quad (2.2)$$

$$F = -a_0 [\sin(\omega) \cos(\Omega) + \cos(\omega) \sin(\Omega) \cos(i)], \quad (2.3)$$

$$G = -a_0 [\sin(\omega) \sin(\Omega) - \cos(\omega) \sin(\Omega) \cos(i)]. \quad (2.4)$$

¹<https://gitlab.obspm.fr/gaia/nsstools>

2.2 Binary Detection

In the previous subsection, I mention that some parameters are given in *Gaia* for different binary classifications. Here, I will discuss the four main classifications of binaries. We can classify and name the types of binaries after these detection methods; visual binaries, eclipsing binaries, astrometric binaries and spectroscopic binaries. Each method is discussed separately below, but note that a given binary can have multiple classifications (e.g. a star can be both an eclipsing and a spectroscopic binary).

2.2.1 Visual Binaries

Visual binaries are the simplest to understand - these are systems where both stars can be individually resolved. This requires the stars to be relatively close to us, and quite widely separated (Pettini, 2021). Because of their wide separation, visual binaries will not undergo significant binary interactions as the two stars evolve. α Centauri AB is an example of a visual binary, as both components (α Centauri A and α Centauri B) can be resolved with even a basic telescope - their binary nature being discovered as far back as 1689 (Kameswara-Rao et al., 1984).

If the orbital period (P_{Orb}), distance (d), and orbital inclination (i) of the system is known, the total and individual masses of the system can be deduced. The total mass, M_{Tot} is given as

$$M_{\text{Tot}} = \frac{4\pi^2}{G} \left(\frac{d}{\cos(i)} \right)^3 \frac{\theta'^3}{P_{\text{Orb}}^2}, \quad (2.5)$$

where θ' is the inclination-corrected angular separation (i.e. $\theta' = \theta \cos(i)$), and then the individual masses can be determined using the mass ratio q ;

$$q = \frac{m_2}{m_1} = \frac{\theta_1}{\theta_2}, \quad (2.6)$$

such that we can find m_2 by

$$m_2 = \frac{qM_{\text{Tot}}}{q+1}, \quad (2.7)$$

and subsequently $m_1 = M_{\text{Tot}} - m_2$.

Visual binaries are not in the *Gaia* DR3 binary catalogues, as their periods will be too long. They can however be identified through the common proper motion of the two stars (see e.g. [El-Badry et al. 2021](#)).

2.2.2 Eclipsing Binaries

The two stars in eclipsing binaries are not both individually resolvable, as they're typically very close systems, but the method yields incredibly precise measurements on binary parameters, with precisions typically around $\lesssim 1$ per cent ([Brown et al., 2023](#)). There are a few methods to extracting parameters from eclipsing systems. One method involves using radial velocity measurements (which can be acquired from spectroscopy) along with light curves, and fitting these to models and minimising to determine the goodness of fit (see e.g. [Parsons et al. 2010](#)). [Brown et al. \(2022\)](#) developed an alternative method of acquiring parameters by fitting parameters found through analysis of multi-band light curves, such as those in [Figure 2.1](#), and *Gaia* parallaxes to models. The specifics of how these methods work are beyond the scope of this thesis, but I encourage the reader to read these papers for a more in-depth understanding on how these work if interested.

We generally don't expect to detect the eclipses of WD + FGK binaries in optical wavelengths, as the FGK companion should dominate the flux at these wavelengths and the WD is very small. There are some exceptions to this (see e.g. [Section 4.4.4](#)), as a very hot WD next to a cool K star may contribute enough in the optical for a noticeable effect, though such systems are a rare exception.

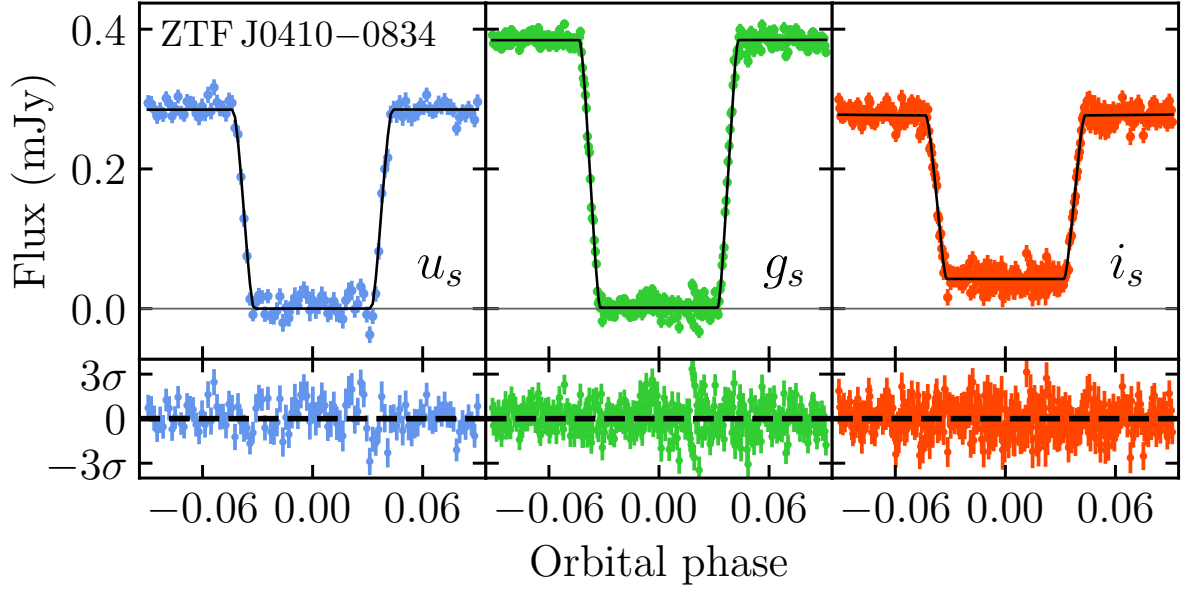


Figure 2.1: ULTRACAM u_s , g_s and i_s light curves of ZTF J041016.82-083419.5 - an eclipsing WD + dM binary. The top panels show the light curves in each band with the best-fitting model plotted in black and the zero flux line shown in grey, with the residuals shown in the bottom panels. Light curves taken from Brown et al. (2023).

2.2.3 Spectroscopic Binaries

Spectroscopic binaries are one of the binary classifications pertinent to Chapter 3 (*Gaia* orbits for known UV excess binaries). Broadly, we can split spectroscopic binaries into two subcategories; double-lined spectroscopic binaries and single-lines spectroscopic binaries.

In double-lined spectroscopic binaries, the observed spectrum will have absorption lines from both stars (Pettini, 2021). As the stars move along their orbits, the absorption lines of the individual stars will vary in wavelength owing to Doppler shift as they move towards or away from the observer, as can be seen in Figure 2.2. The measured Doppler shifts provide lower limits on the velocities of the stars, as the inclination of the system is unknown. The total mass of the system can be found by Keplers laws, such that

$$M_{\text{Tot}} = \frac{P_{\text{Orb}} (K_1 + K_2)^3}{2\pi G \sin^3(i)} (1 - e^2)^{3/2}, \quad (2.8)$$

where K_1 and K_2 are the peak radial velocities of the two stars and e is the eccentricity of the system. The individual masses can then be determined using the mass ratio, as with visual binaries, where

$$q = \frac{m_2}{m_1} = \frac{K_1}{K_2}. \quad (2.9)$$

However, since the inclination i of the system is usually unknown for spectroscopic binaries, this only gives lower limits on the masses.

Single-lined spectroscopic binaries are slightly different. In these cases, only one set of absorption lines are visible in the spectrum of the binary, though they are still Doppler shifted. This is caused by the star still moving in a binary orbit, indicating the presence of a non-optically luminous companion. In these cases, K_2 cannot be directly measured. However, we can substitute in the relation $K_2 = K_1 m_1 / m_2$ from the mass ratio, resulting in the equation for the total mass becoming

$$M_{\text{Tot}} = \frac{P_{\text{Orb}}}{2\pi G} \frac{K_1^3}{\sin^3(i)} \left(1 + \frac{m_1}{m_2}\right)^3 (1 - e^2)^{3/2}. \quad (2.10)$$

We expect that WD + FGK binaries should be single-lined spectra, and will be an important population of such binaries, as is expanded upon in Chapter 3 (*Gaia* orbits for known UV excess binaries).

2.2.4 Astrometric Binaries

Astrometric binaries are the other binary classification pertinent to Chapter 3 (*Gaia* orbits for known UV excess binaries). These binaries consist of a optically luminous star and a non-optically luminous companion. The mass of the companion causes the centre of mass of the binary to be shifted away from the photocentre of the system, which is approximated by the optically luminous star, an example of which can be seen in Figure 2.3. This offset of the photocentre from the centre of mass causes the

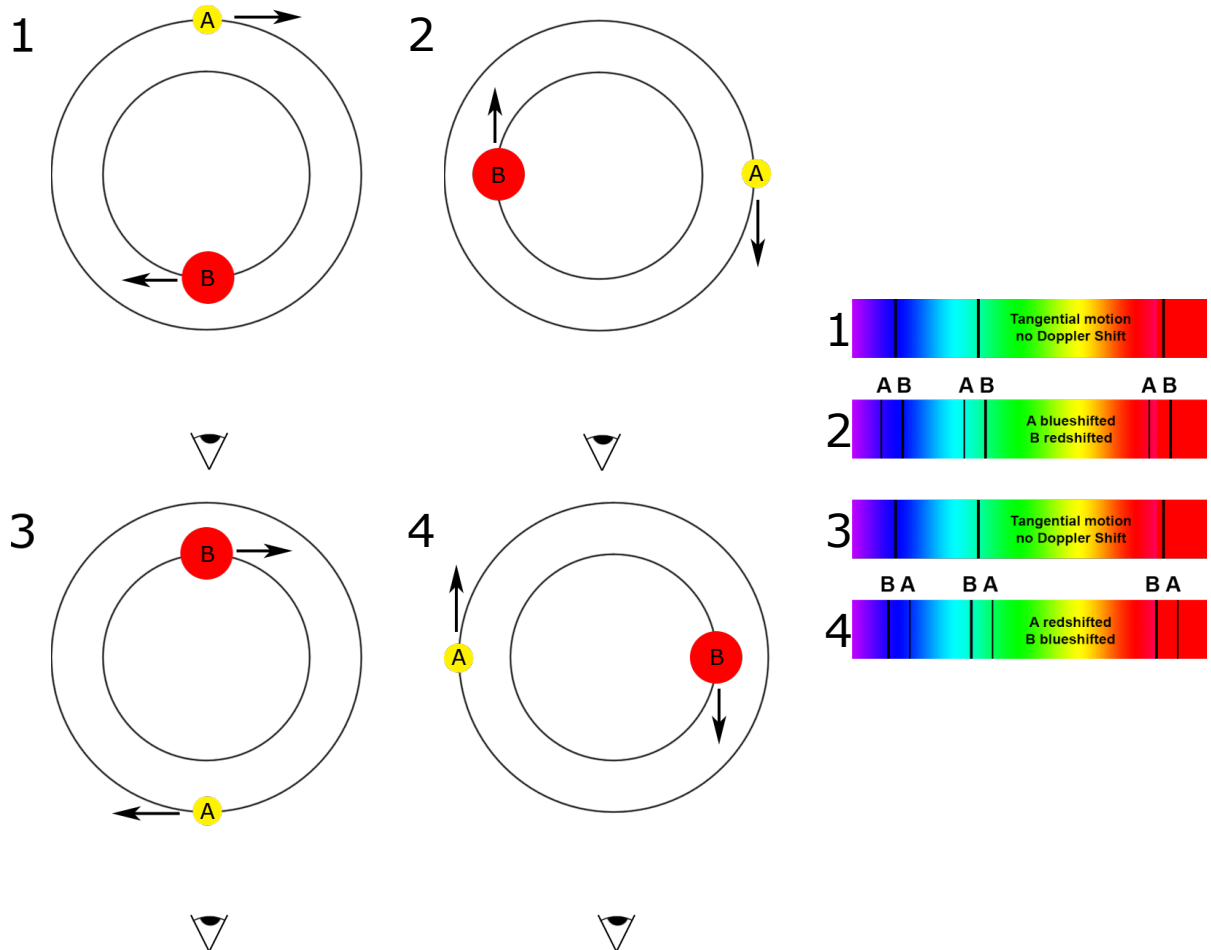


Figure 2.2: Illustration of how the motion of binary components changes lines observed in the spectrum of a binary. In position 1, both stars are moving tangentially to the observers line of sight, so there is no Doppler shift. In position 2, star A is moving towards the observer and star B away from the observer, leading to the lines of star A being blueshifted and the lines of star B being redshifted, so these their lines separate on the spectra as can be seen on the right. Position 3 has both stars back moving tangentially relative to the line of sight of the observer, as in position 1, and in position 4 star A is moving away so is redshifted, and star B is moving towards, so is blueshifted - the opposite of position 2.

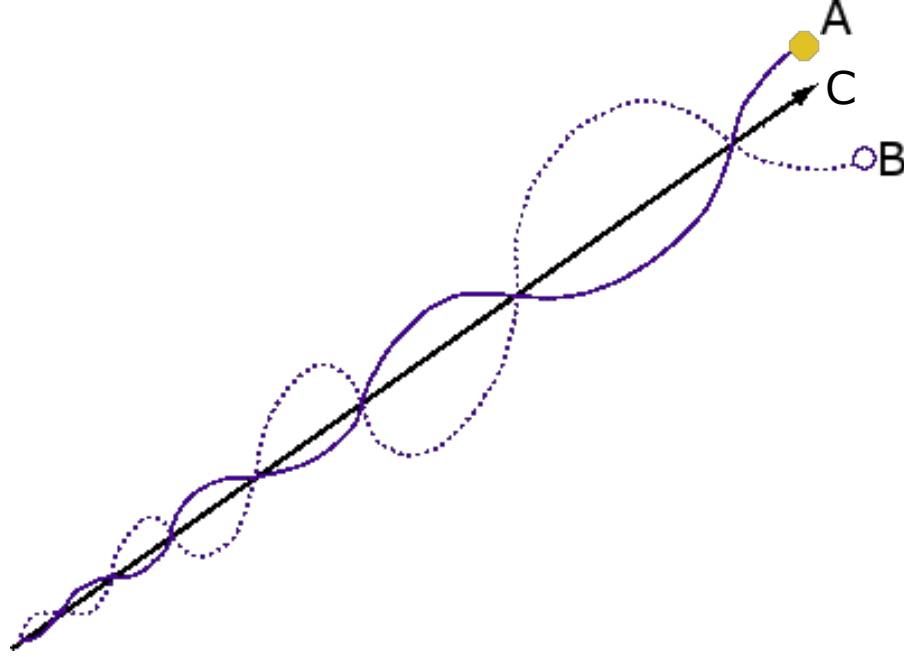


Figure 2.3: An Illustration of astrometric motion. The mass of the non-optimally luminous companion (B) causes the centre of mass (C) to be offset from the photocentre of the system, approximated by the optically luminous companion (A). This causes the optically luminous star to ‘wobble’ along its proper motion. Figure adapted from Pogosyan (2010).

photocentre to ‘wobble’ along its proper motion.

Although astrometry has been used to detect binaries since the 19th century (van de Kamp, 1975), it was hindered by seeing. Space telescopes (such as *Hipparcos* (Perryman et al., 1997) and *Gaia*) overcome these effects, and allowed for easier and more precise astrometric measurements. Using *Gaia* DR3, Shahaf et al. (2019) built a method of determining the mass of the non-luminous component of the binary using a parameter they named the astrometric mass-ratio function, $\mathcal{A}$, defined by

$$\mathcal{A} \equiv \frac{q}{(1+q)^{\frac{2}{3}}} \left(1 - \frac{\mathcal{S}(1+q)}{q(1+\mathcal{S})} \right) = \frac{a_0}{\varpi} m_1^{-\frac{1}{3}} P_{\text{Orb}}^{-\frac{2}{3}}, \quad (2.11)$$

where $\mathcal{S}$ is the ratio of fluxes of the two component stars, a_0 is the angular semi-major axis, and ϖ is the parallax of the system. We expect a significant number of WD + FGK binaries should be astrometric binaries.

2.3 Model Fitting

With the types of binaries established, and how to extract component masses, we can discuss how to get other stellar parameters by fitting to models. In both [Chapter 3](#) (*Gaia* orbits for known UV excess binaries) and [Chapter 4](#) (The *Gaia-GALEX* UV Excess Sample for systems within 350 pc), we need to fit parameters to models in order to extract model parameters, either for the luminous companion or for the WD. Throughout this thesis, we use both the He-core models of [Althaus et al. \(2013\)](#)² and the DA CO-core models of [Bédard et al. \(2020\)](#)³. The specifics of each fit, including which parameters are being fit, are explained in more detail in [Chapter 3](#) (*Gaia* orbits for known UV excess binaries) and [Chapter 4](#) (The *Gaia-GALEX* UV Excess Sample for systems within 350 pc) respectively. In [Chapter 3](#) (*Gaia* orbits for known UV excess binaries) we use nested sampling in order to match against a grid of stellar model parameters, whilst in [Chapter 4](#) (The *Gaia-GALEX* UV Excess Sample for systems within 350 pc) we use a goodness of fit test in order to fit to WD models.

2.3.1 Nested Sampling

Nested sampling ([Skilling, 2004](#)) uses Bayesian inference in order to scan parameter space for the highest likelihood match between the data and the model for given parameters. Bayesian inference is somewhat beyond the scope of this thesis, so the following overview will oversimplify in places. Baye’s theorem states that

$$P(\Theta) = \frac{L(\Theta)\pi(\Theta)}{\mathcal{Z}}, \quad (2.12)$$

where $P(\Theta)$ is the posterior probability of parameters Θ given a dataset and model, $L(\Theta)$ is the likelihood (the probability of the dataset, given the parameters and the model),

²<http://evolgroup.fcaglp.unlp.edu.ar/TRACKS/newtables.html>

³<https://www.astro.umontreal.ca/~bergeron/CoolingModels/>

$\pi(\Theta)$ is the prior (the likelihood of the parameters given the model) and $\mathcal{Z}$ is the Bayesian evidence (the probability of the data given the model). Given $\mathcal{Z}$ is independent of the parameters Θ , it is generally ignored in parameter estimation. However, determining the best model for the data, it is the crucial factor (Feroz & Hobson, 2008). The evidence $\mathcal{Z}$ can be found as

$$\mathcal{Z} = \int L(\Theta)\pi(\Theta) d^D\Theta \quad (2.13)$$

where D is the dimensionality of the parameter space.

Nested sampling simplifies finding $\mathcal{Z}$ by transforming it from a multidimensional problem into a one-dimensional problem by exploiting the relationship between the likelihood $L(\Theta)$ and the prior volume X , defined by

$$dX = \pi(\Theta) d^D\Theta, \quad (2.14)$$

which simplifies the evidence integral to simply

$$\mathcal{Z} = \int_0^1 L(X)dX \approx \sum_{i=1} L_i w_i, \quad (2.15)$$

where w_i is a weighting factor. Feroz & Hobson (2008) uses the trapezium rule, for which

$$w_i = \frac{1}{2} (X_{i-1} - X_{i+1}). \quad (2.16)$$

This is done in the background of the ISOCHRONES package⁴ (Morton, 2015) used in Chapter 3 (*Gaia* orbits for known UV excess binaries), using the PYMULTINEST module⁵ (Buchner et al., 2014) to implement a MultiNest algorithm (Feroz & Hobson, 2008; Feroz et al., 2009). To oversimplify, MultiNest keeps a fixed number of ‘live points’ drawn at random from priors and sorted by likelihood calculated by nested sampling. It

⁴<https://github.com/timothydmorton/isochrones>

⁵<https://github.com/JohannesBuchner/PyMultiNest>

removes the lowest likelihood point and re-samples until a new, higher probability point is found, until the remaining number of points to draw from becomes negligible.

2.3.2 Goodness of Fit

Goodness of fit is a measure of how well a model matches to a dataset. There are many different tests to determine goodness of fit, with one of the most common being χ^2 tests. There are a few varieties of χ^2 tests, with the first being proposed by [Pearson \(1900\)](#), given as

$$\chi^2 = \sum_i \frac{(O_i - Np_i)^2}{Np_i}, \quad (2.17)$$

where O is the count number of the observed result and N the total sample size, such that $N = \sum_i O_i$, and p_i is the probability of the event. The classical example is rolling a fair six-sided die N times, where here O_i would be the number of occurrences of any one side being rolled (say, O_1 would be the number of times the value ‘1’ was rolled). For a fair die, the probability p_1 would be $1/6$.

In [Chapter 4 \(The *Gaia*-GALEX UV Excess Sample for systems within 350 pc\)](#), we use a reduced χ^2 model. Here, we consider the χ^2 per degree of freedom ν , i.e.

$$\chi_\nu^2 = \frac{\chi^2}{\nu} \quad (2.18)$$

where here, χ^2 is instead calculated from an observed value $\mathcal{O}$ against model value $\mathcal{M}$ and the variance σ^2 , such that

$$\chi^2 = \sum \frac{(\mathcal{O} - \mathcal{M})^2}{\sigma^2}. \quad (2.19)$$

In order to maximise our goodness of fit, we need to find the model which produces the smallest χ_ν^2 . There are a few methods of doing this, though we use a least squares fit

using the SCiPY function `leastsq`. This function serves as a wrapper to the `lmdif`⁶ and `lmder`⁷ algorithms of MINPACK (More et al., 1980), which implements a levenberg-marquardt method to find the lowest value - the scope of which is beyond the scope of this thesis. For an explanation of this method, see e.g. (Gavin, 2026). To oversimplify, `leastsq` finds a local minimum in the input function (in our case, our χ^2_ν equation) based on user-input initial ‘guess’ parameters.

⁶<https://www.math.utah.edu/software/minpack/minpack/lmdif.html>

⁷<https://www.math.utah.edu/software/minpack/minpack/lmder.html>

Chapter 3

Gaia orbits for known UV excess binaries.

“ Somewhere deep in the slow,
eternal dance of the heavens
drifts a planet called simply ‘Earth’ ”

— Ninja Sex Party, *6969*, 2015

Declaration: Part of the science in this chapter was done by a co-author. The UV spectral analysis of the White Dwarf (WD)s was done by Dr. Odette Toloza, for which I had no hand in.

Chapter Summary

WDs with an F, G or K type companion represent the last common ancestor for a plethora of exotic systems throughout the Galaxy (see Section 1.3.4), though to this point very few of them have been fully characterised in terms of orbital period and component masses, despite the fact several thousand have been identified. *Gaia* Data Release (DR)3 has examined many hundreds of thousands of systems, and as such we can use this, in conjunction with previous Ultraviolet (UV) excess catalogues, to perform Spectral Energy Distribution (SED) fitting in order to obtain a sample of 203 binaries likely to contain a WD, complete with orbital periods, and either a direct measurement of the component masses for astrometric systems, or a lower limit on the component masses for spectroscopic systems. Of this sample of 202, 4 have previously been observed with *Hubble Space Telescope* (HST) spectroscopically in the UV, which has confirmed the presence of a WD, and we find excellent agreement between the dynamical and spectroscopic masses of the WDs in these systems. We find that WD + FGK binaries can have a wide range of orbital periods, from less than a day to many hundreds of days. A large number of our systems are likely post-Stable Mass Transfer (SMT) systems based on their mass/period relationships, while others are difficult to explain either via Stable Mass Transfer (SMT) or standard Common Envelope Evolution (CEE).

3.1 Introduction

WDs are the last stage of the evolution of low to intermediate mass stars, of initial mass around $\sim 0.85 - 9 M_{\odot}$ (Kepler et al., 2007; Cummings et al., 2018). It has been found through observations (e.g. Holberg 2009; Toonen et al. 2017), that around 18-26 per cent of WDs are in a binary system, meaning that the WD evolved in proximity to a companion.

If the initial binary system had an orbital period, P , of less than roughly 10^4 d, then it is likely that the two stars interacted as the WD progenitor evolved off the main-sequence (Willems, B. & Kolb, U., 2004). A possible interaction would be a CE phase (Paczynski, 1976). Here, as the more massive star's envelope expands and overflows its Roche lobe, it begins unstably shedding matter. In this process, the less massive star also overfills its Roche lobe, resulting in the formation of a CE around the core of the donor and the less massive companion. This causes them to spiral inward. If enough orbital energy is transferred to the envelope to unbind and eject it, a post-CE system with a shorter period is formed (Rebassa-Mansergas et al., 2008; Nebot Gómez-Morán et al., 2011).

The specific dynamics of the CE phase are difficult to reproduce with hydrodynamical modelling (Passy et al., 2012; Ohlmann et al., 2016; Ondratschek et al., 2022; Moreno et al., 2022). As such, typically a simplified equation involving the CE efficiency, α_{CE} , is used instead - where α_{CE} is the fraction of the change in orbital energy used to unbind the envelope. Therefore, a lower efficiency implies a greater reduction in the orbital period. Zorotovic et al. (2010) has found a value of $\alpha_{\text{CE}} \approx 1/3$ through observations of WD + dM binaries, with similarly low efficiencies being found for WD + BD binaries (Zorotovic & Schreiber, 2022) and close low mass WD + WD binaries (Scherbak & Fuller, 2023) - though it is uncertain if such a value is universal. If this is the case, then most WD + FGK systems would be expected to emerge from the CE phase with periods too

short for them to survive a second CE phase, meaning that forming double-degenerate systems via this pathway would be extremely challenging. Indeed, it was this issue that led to the creation of the so-called γ formalism (Nelemans et al., 2000). Gamma formalism, also called “CE without spiral in”, is stable but highly non-conservative mass transfer. However, there are alternative channels to the creation of longer period WD + FGK binaries that do not involve a CE phase, such as the SMT channel (Webbink, 2008).

SMT, as proposed by Webbink (2008), is thought to occur when the masses of the two stars are very similar, or if the system comes into contact when the donor star is on, or has just left, the main sequence. In this scenario, the less massive star is likely to successfully accrete the mass overflowing from the more massive companion at a steady rate, which can lead to a widening of the binary if the transfer is non-conservative (Podsiadlowski, 2014). This would leave the system with a wide enough period to survive a CE phase without merging when the lower mass star evolves, which can lead to double-degenerate systems, a progenitor for thermonuclear supernovae. It is not yet understood how conservative this mechanism is in practice, with Kawahara et al. (2018) suggesting the mass transfer is usually non-conservative, whilst Podsiadlowski (2014) suggests a near fully conservative transfer.

Until recently, the majority of WD + FGK binaries with known orbital periods (e.g. Parsons et al. 2015; Hernandez et al. 2020, 2022a; Lagos et al. 2022; Hernandez et al. 2022b) were short period systems of around $\sim 0.5 - 2.5$ d, which can be reproduced with the same CE efficiency as used for WD + dM binaries ($\alpha_{\text{CE}} \approx 1/3$). These short period systems can go on to become cataclysmic variables or supersoft X-ray source systems. Longer period systems had proven more elusive, though there were a small number published (Kruse & Agol, 2014a; Kawahara et al., 2018; Masuda et al., 2019; Parsons et al., 2023; Yamaguchi et al., 2024a), with Shahaf et al. (2024) identifying a few thousand WD + FGK candidates in *Gaia* DR3, with periods around $\approx 100 - 1000$ d

- though this sample has yet to be explored in great detail. These longer period systems are likely the progenitors of double degenerate systems and symbiotic binaries (Zorotovic et al., 2014). Thus far, these systems have not been able to be reconstructed with the CE efficiency of 1/3 as found by Zorotovic et al. (2010), or even with $\alpha_{\text{CE}} = 1$ although see Belloni et al. (2024) for a potential solution to this. It is possible for some these to be post-SMT systems (Parsons et al., 2023), but many of these longer period systems are a challenge to produce even by this channel. Given that WD + FGK binaries are the last common ancestor to a number of exotic phenomena, such as the before-described cataclysmic variable and double degenerate systems - they are thus important to study and understand. It is possible to find WD + FGK binaries by looking for sources that appear to be F, G or K type stars in the optical, but have a flux excess in the UV, as a WD would be fully obscured by a F, G or K binary companion in optical wavelengths, but in turn outshine them in the UV owing to their high residual temperatures. Given the importance of such objects, *The White Dwarf Binary Pathways Survey* has set about trying to catalogue the titular systems and determine their formation channels.

Gaia DR3 (hereafter *Gaia*) can be used as an important tool for getting a large number of binary parameters, such as the orbital period, with little effort, as it possesses accurate orbital period measurements for a large number of systems, bypassing the need for extensive follow-up observations to identify and characterise WD + FGK binaries. In this paper we probe *Gaia* for previously established UV excess binaries (Parsons et al. 2016; Rebassa-Mansergas et al. 2017; Ren et al. 2020) to determine their binary and stellar parameters, most crucially their orbital periods and component masses, so that we can investigate their past and future evolution.

3.2 Target Selection

In order to ensure a relatively clean sample of WD + FGK binaries, we make cuts to remove as many sources of contamination as possible so that we are only working with systems where a WD + FGK binary is likely, as our method of identifying these systems by their UV excess is only valid for these systems, where the luminous companion completely dominates in optical wavelengths but where the WD causes a notable excess in the UV.

Taking the *RA*dial *VE*locity *EX*periment (*RAVE*) sample of 430 candidates from Parsons et al. (2016), 1549 candidates from the *LA*rge *SK*y *AR*ea *MU*lti-*OB*ject *FI*ber *SP*ectro-*SC*opic *TE*lescope (*LAMOST*) sample of Rebassa-Mansergas et al. (2017) and the sample of 775 candidates from the *TY*cho-*GA*ia *AS*trometric *SO*lution (*TGAS*) sample of Ren et al. (2020), we matched these 2754 candidates to the *Gaia* source catalogue using positional crossmatching. These samples were constructed using *RAVE* DR4, *LAMOST* DR4 and *TGAS*; crossmatching them with *GALEX* UV data in order to identify candidate UV excess sources. These three samples were, at the time of writing Garbutt et al. (2024), the best and largest sample of WD + FGK candidates.

To this point, these samples may contain poor *Gaia* matches and stars that are not of the F, G or K spectral classes. To resolve this, we implemented a cut to our selection criteria - removing systems that were a magnitude bluer than the MS track as defined by the MIST¹ Zero-Age Main Sequence (ZAMS) isochrone (Dotter, 2016; Choi et al., 2016; Paxton et al., 2011, 2013, 2015) for a solar metallicity star using *Gaia* G and $G_{BP} - G_{RP}$ magnitudes, which removed 6 systems from the *RAVE* sample of Parsons et al. (2016), 204 from the *LAMOST* sample of Rebassa-Mansergas et al. (2017) and 1 systems from the *TGAS* sample of Ren et al. (2020). We made no attempts to exclude M Dwarf (dM) systems, as non-active acrodm stars are too faint to be detected in *GALEX*, and

¹<https://waps.cfa.harvard.edu/MIST/>

the selection criteria of the original samples of [Parsons et al. \(2016\)](#), [Rebassa-Mansergas et al. \(2017\)](#) and [Ren et al. \(2020\)](#) should have removed such systems. For the astrometric binaries, we used the parallax values from the `gaiadr3.nss_two_body_orbit` catalogue throughout this paper. This removed sources where the compact object may contribute to the optical flux, such as WD + dM or hot subdwarf + FGK binaries. Whilst measures were taken by [Parsons et al. \(2016\)](#), [Rebassa-Mansergas et al. \(2017\)](#) and [Ren et al. \(2020\)](#) to remove M stars, some have since been flagged by *Gaia*, while no efforts were taken to remove hot subdwarf systems in the original studies.

Following the removal of these contaminants, along with the removal of duplicates within each survey, we crossmatched the surveys with the `gaiadr3.nss_two_body_orbit` catalogue, which provided us with orbital solutions for systems identified as astrometric, spectroscopic or eclipsing binaries. The optical colour-magnitude diagrams of each of the surveys, colour-coded by their orbital period, can be observed in Figure 3.1. It is worth noting that the presence of giant stars (the outcrop of points on the luminous, redder end of the main sequence track) in the *RAVE* and *LAMOST* samples was somewhat unexpected, as each had taken measures to avoid giant stars, with the other points sitting between ~ 0.3 and ~ 1.8 in the $G_{BP} - G_{RP}$ domain, roughly where we would expect for F, G and K stars along the main sequence track. We can see that, in contrast to previous results, there are a large number of long-period systems² found across all three samples, with *TGAS* especially being dominated by periods in excess of 100 d. It can also be observed that the *TGAS* sample does not stretch as far down the main sequence track as much as either the *RAVE* or *LAMOST* samples, which could be down to selection bias, as [Ren et al. \(2020\)](#) was conducting a sample of WD + AFGK binaries opposed to just WD + FGK binaries, which may have skewed their selection away from the fringe cases of late-K stars, or owing to the initial selection that used DR1 as the

²We refer to systems with orbital periods in the order of ~ 100 -1000 d as long-period binaries, as opposed to wide binaries which have periods of many years and will not have had any binary interactions.

Table 3.1: A table breaking down the different solution types found across [Parsons et al. \(2016\)](#), [Rebassa-Mansergas et al. \(2017\)](#) and [Ren et al. \(2020\)](#) (given the short-hand form of *RAVE*, *LAMOST* and *TGAS* respectively). The numbers given outside the brackets are the numbers in our final sample of WD + FGK candidates, whilst those given in the brackets represent the number found within the `gaiadr3.nss_two_body_orbit` catalogue (or flagged as ECL in the `gaiadr3.vari_classifier_result` catalogue. The total number of candidates here listed is 211, with the discrepancy between this number and our quoted number of 202 candidates arising from duplicates between the samples. Additionally, the total number of objects stated here from the `gaiadr3.nss_two_body_orbit` catalogue occur before our listed quality control cuts.

Solution / Systems	<i>RAVE</i>	<i>LAMOST</i>	<i>TGAS</i>
Orbital	4 (7)	24 (30)	18 (26)
OrbitalTargetedSearch	0	0	1 (2)
OrbitalTargetedSearchValidated	0 (1)	0	0
SB1	25 (37)	25 (33)	56 (73)
SB2	0	0	0 (6)
SB2C	0	0	0 (4)
AstroSpectroSB1	12 (14)	8 (9)	38 (42)
Eclipsing Binaries	0 (0)	0 (1)	0 (4)
Total	41 (59)	57 (72)	113 (153)

original sample.

The solutions found within the `gaiadr3.nss_two_body_orbit` catalogue are: `Orbital`, `OrbitalAlternative`, `OrbitalTargetedSearch`, `OrbitalTargetedSearchValidated` (all four of which are astrometric fits, and will hereafter be referred to as astrometric systems), `EclipsingBinary`, `EclipsingSpectro` (which are both visually eclipsing systems), `SB1`, `SB2`, `SB1C`, `SB2C` (which are all spectroscopic systems - the number referring to how many resolved lines are present, and the C indicating a circular orbit), and `AstroSpectroSB1` (which is a combined astrometric and single-line spectroscopic model, but for our purposes can be counted as solely astrometric). The breakdown of how many systems belonged to each solution type is detailed in Table 3.1, along with the number of eclipsing binaries found by cross-matching with the `gaiadr3.vari_classifier_result` catalogue.

With the solution types known, we can make further cuts in accordance with [Gaia](#)

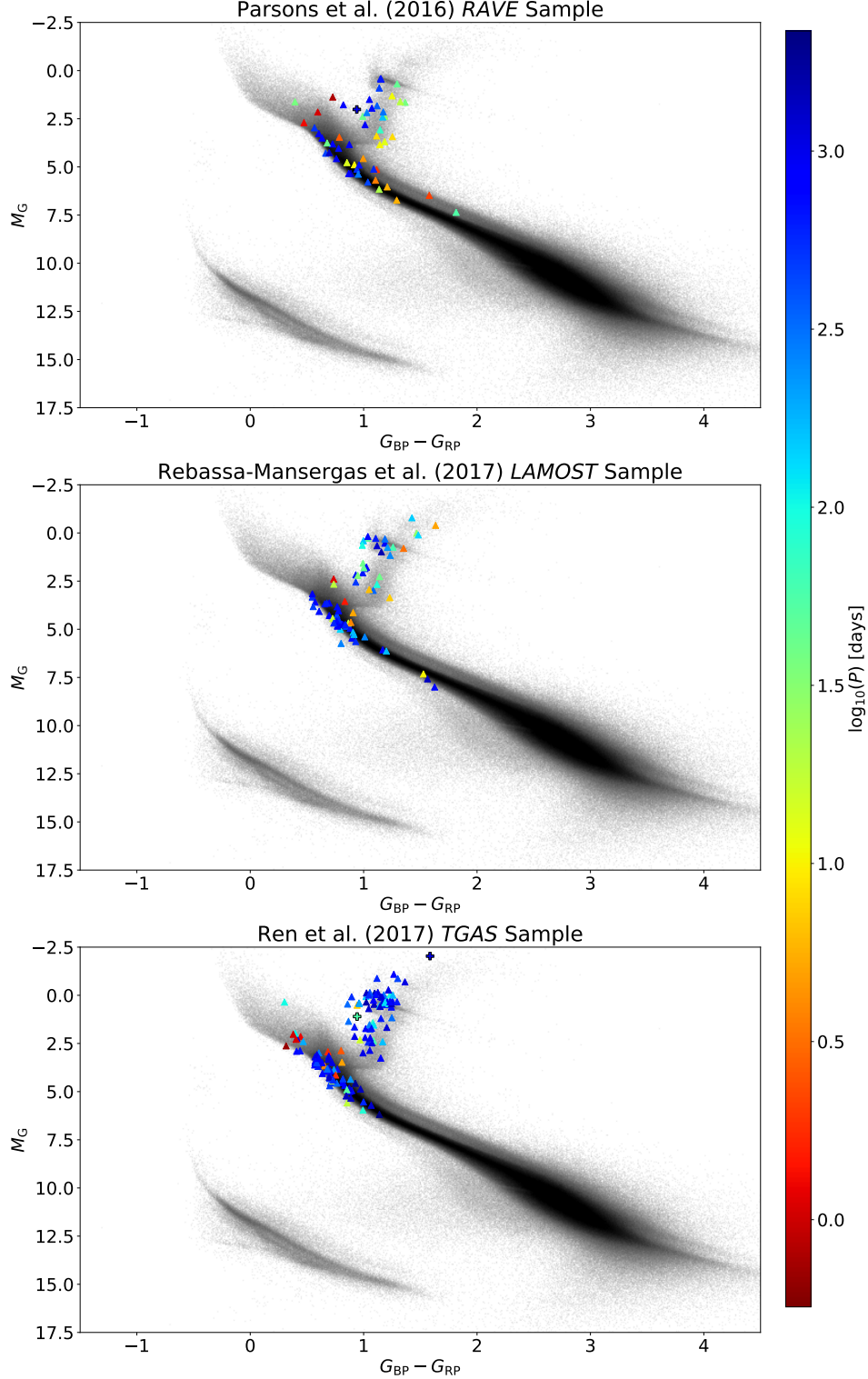


Figure 3.1: Optical colour-magnitude diagrams using *Gaia* G , BP and RP magnitudes, split by the three surveys of Parsons et al. (2016), Rebassa-Mansergas et al. (2017) and Ren et al. (2020). The points are colour-coded by the $\log_{10}$ of their period. The background points are a randomly selected sample of stars from *Gaia* within 250 pc and with a parallax-over-error greater than 20. The larger, circular points represent candidate hot subdwarf binary systems (see Section 3.5.5).

Collaboration et al. (2023c). Which is to say ‘Orbital’ systems were excluded if;

- `phot_g_mean_mag` > 19,
- `ipd_frac_multi_peak` ≥ 2 ,
- `ipd_gof_harmonic_amplitude` > 0.1,
- `visibility_periods_used` < 11,
- $C^* < 1.645\sigma_{C^*}$ ³,

where `ipd_frac_multi_peak` is the percent of successful [Image Parameter Determination \(IPD\)](#) with more than one peak, `ipd_gof_harmonic_amplitude` is the amplitude of the the [IPD](#) goodness of fit vs the position angle of the associated scan, and `visibility_periods_used` is the number of visibility periods used in the astrometric solution. For SB1 and SB1C, the criteria for exclusion from [Gaia Collaboration et al. \(2023c\)](#) are;

- `rv_renormalised_gof` < 4,
- `rv_nb_transits` < 11,
- $3875 > \text{rv_template_teff} > 8125$,

where `rv_renormalised_gof` is the renormalised goodness of fit of the radial velocity measurements, `rv_nb_transits` is the number of transits used in the calculation of the radial velocity, and `rv_template_teff` is the effective temperature (T_{eff}) of the template used in the radial velocity calculations.

Since we are interested in systems where the optical flux comes exclusively from one star, systems flagged as `EclipsingBinary`, `EclipsingSpectro`, `SB2` or `SB2C` were

³Here, C^* is the corrected *BP* and *RP* flux excess and σ_{C^*} is its associated uncertainty, as defined by [Riello et al. \(2021\)](#).

dropped from the samples, as the Eclipsing systems by their nature contain stars bright enough to show an eclipse (which would not be possible except for very hot WDs with very late-K stars), and the double-lines spectroscopic by their nature have two optically luminous components, which would not be the case for a WD + FGK binary. Additionally, systems which were flagged as ECL (shorthand for eclipsing) in the `gaiadr3.vari_classifier_result` were dropped, for the same reason as stated for the eclipsing systems within `gaiadr3.nss_two_body_orbit`. After these systems are removed and the above astrometric and spectroscopic cuts are applied, we are left with 55 systems from the *RAVE* sample of Parsons et al. (2016), 71 from the *LAMOST* sample of Rebassa-Mansergas et al. (2017) and 128 from the *TGAS* sample of Ren et al. (2020). It should be noted that there are systems that lie across multiple of these surveys, with there being a total of 246 systems after this criterion is taken into account.

For the astrometric binaries, we used the python NSS TOOLS⁴ (Halbwachs et al., 2022) in order to transform the given orbital Thiele-Innes constants, denoted as A , B , F and G , and defined by;

$$A = a_0 [\cos(\omega) \cos(\Omega) - \sin(\omega) \sin(\Omega) \cos(i)], \quad (3.1)$$

$$B = a_0 [\cos(\omega) \sin(\Omega) + \sin(\omega) \cos(\Omega) \cos(i)], \quad (3.2)$$

$$F = -a_0 [\sin(\omega) \cos(\Omega) + \cos(\omega) \sin(\Omega) \cos(i)], \quad (3.3)$$

$$G = -a_0 [\sin(\omega) \sin(\Omega) - \cos(\omega) \cos(\Omega) \cos(i)], \quad (3.4)$$

where a_0 is the angular semi-major axis of the system, ω is the argument of periapsis, Ω is the longitude of the ascending node and i is the inclination; into the Campbell parameters (a_0 , ω , Ω and i), the most pertinent of which being the angular semi-major axis, a_0 of the system.

⁴<https://gitlab.obspm.fr/gaia/nsstools>

3.3 Stellar Parameters

With our samples cleaned and orbital parameters acquired, we can set about obtaining the parameters of the luminous star⁵ and then the WD. This will allow us to probe the evolution of these systems, along with flagging additional contaminants.

3.3.1 LS parameters

Whilst *Gaia* does give estimates for stellar parameters in their `gaiadr3.astrophysical_parameters`, `gaiadr3.astrophysical_parameters_supp` and `gaiadr3.binary_masses` catalogues, these are not necessarily accurate and are not available for all systems. As such, we obtain properties for the luminous component of the binary system using [Spectral Energy Distribution \(SED\)](#) fitting with the python ISOCHRONES package⁶ ([Morton, 2015](#)). We perform fitting using synthetic u, g, r, i, z magnitudes from `gaiadr3.synthetic_photometry_gspc` where available, g, r, i, z if there was no u measurement, or G, BP and RP as a last resort if there was no synthetic photometry available - alongside $J, H, Ks, W1$ and $W2$ magnitude measurements taken from *2MASS* ([Skrutskie et al., 2006](#)) and *All-WISE* ([Cutri et al., 2021](#)) *Gaia* match catalogues (`gaiadr1.tmass_original_valid` with `gaiadr3.tmass_psc_xsc_best_neighbour` and `gaiadr1.allwise_original_valid` with `gaiadr3.allwise_best_neighbour` respectively). SED fitting is not without its drawbacks - it relies on assumptions about its inputs and our results without u band synthetic photometry in particular may not be able to constrain the effective temperature, $T_{\text{eff,LS}}$ very well. Ultimately, spectroscopic data is needed to fix these parameters properly.

We place priors on our fit, these include a Gaussian prior on parallax based on *Gaia* measurements, a flat prior on extinction, based on the values and uncertainties from the

⁵Luminous star here referring to the more optically luminous companion, which can be either a main sequence or an evolved star.

⁶<https://github.com/timothydmorton/isochrones>

3d dustmaps of STILISM [Capitanio et al. \(2017\)](#), with a Jeffreys prior, as defined by

$$P(E(B - V)) \propto E(B - V)^{1/2}. \quad (3.5)$$

where we place a lower bound of 10^{-4} and an upper bound at the maximum value found in the system’s direction within stilism. We also used the [Casagrande et al. \(2011\)](#) metallicity prior. We then fitted our data to MIST isochrones ([Dotter, 2016](#); [Choi et al., 2016](#); [Paxton et al., 2011, 2013, 2015](#)) using a Markov Chain Monte Carlo (MCMC) method with 3000 live points per fit. For our initial fits we assumed that all the flux comes from the optically luminous star (hence why we did not include UV measurements in our fit), however there may be cases where the WD component could contribute to the optical flux, particularly at the shortest wavelengths. Using the WD parameters derived in Section 3.3.2, we can estimate what the WD contribution is likely to be at optical wavelengths and found that this reaches around 5 per cent at most. We ran additional fits to re-derive the luminous star parameters accounting for the WD contribution and found that even in the worst cases the resulting difference in the parameters was far smaller than the uncertainties on the original measurements.

Some non-WD companions (usually low mass active stars) can contaminate UV excess samples such as the ones we are dealing with. These contaminants can be found by looking for infrared excesses, as a low-mass star will contribute a non-negligible amount of flux at longer wavelengths. To identify these kinds of contaminants, we fitted an SED with a two component fit using the ISOCHRONES package. We then performed a log-likelihood ratio test on every system comparing their single and double star model fits, flagging systems where the double fit was more likely (comprising 18 systems) as likely contaminants. We also note that it is possible to hide relatively high mass main-sequence companions (e.g. A-type stars) next to giants, which may result in the detection of a UV excess, while having little effect on the optical colours of the system. However, these

stars have masses typically much higher than the Chandrasekhar mass and so can be removed with a simple upper limit on the companion mass. Ultimately, of the combined sample of 246 systems, we have 44 contaminants (the 18 systems where the double fit was preferred, 4 where we find the system would not be thermally stable, discussed later in Section 3.3.2, 14 we find to be too young to be a WD, 3 sdOB candidates, 4 systems where the WD mass was above $1.4 M_{\odot}$, and one where we identify it is an active star through it's HST spectra), giving us a contamination rate of ~ 17 per cent, which is fairly consistent with the previous works in this series.

This gave us values describing the luminous companion - its effective temperature, the log of its surface gravity, $\log(g)_{\text{LS}}$, its radius, R_{LS} , and most importantly, its mass, M_{LS} . It also provided values for metallicity, $\log(Z)_{\text{LS}}$, though the SED is insensitive to this parameter and is in many cases unconstrained, so we do not include it here.

3.3.2 WD parameters

By using the parameters of the luminous companion determined by SED fitting with the *Gaia* orbital parameters, we can determine the properties of the hidden companion, assumed to be a WD. This is done using a different approach depending on whether the system is an astrometric binary or a spectroscopic binary, so they will be discussed separately.

Astrometric binaries

We can determine the mass of the unseen companion within an astrometric binary using the astrometric mass function, $\mathcal{A}$, described by Shahaf et al. (2019),

$$\mathcal{A} \equiv \frac{q}{(1+q)^{\frac{2}{3}}} \left(1 - \frac{\mathcal{S}(1+q)}{q(1+\mathcal{S})} \right) = \frac{a_0}{\varpi} M_{\text{LS}}^{-\frac{1}{3}} P^{-\frac{2}{3}}, \quad (3.6)$$

in which a_0 is the angular semi-major axis, ϖ is the parallax, P is the period, q is the mass ratio of the system, such that

$$q = \frac{M_{\text{WD}}}{M_{\text{LS}}}, \quad (3.7)$$

and $\mathcal{S}$ is the ratio of the intensities of the components, which we take as zero as our underlying assumption is that 100 per cent of the optical flux is contributed by the luminous companion.

It is thus straightforward to extract the mass of the WD by solving the astrometric mass function. We also propagated all uncertainties through this function to estimate errors on the WD masses. Any systems where the unseen companion has a mass clearly above the Chandrasekhar mass limit were flagged as contaminants.

Spectroscopic binaries

Spectroscopic binary systems are instead determined by the binary mass function determined from Kepler's laws,

$$\frac{M_{\text{WD}}^3 \sin^3(i)}{(M_{\text{WD}} + M_{\text{LS}})^2} = \frac{K^3 P}{2\pi G} (1 - e^2)^{\frac{3}{2}}, \quad (3.8)$$

where K is the radial velocity semi-amplitude and e is the eccentricity. It should be noted that in general the inclination, i , is unknown for spectroscopic systems. This limits us to only getting a minimum WD mass estimate for these systems by assuming $\sin i = 1$, which will limit the conclusions that can be drawn from these systems.

WD temperature estimates

With the masses known (or lower limits in the case of the spectroscopic systems), and Far Ultraviolet (*FUV*) magnitudes measured by *GALEX* (Martin et al., 2005a), we

can set about obtaining estimates of the effective temperature of the WD $T_{\text{eff,WD}}$ (and consequently the log of its surface gravity, $\log(g)_{\text{WD}}$) and its cooling age, τ_{cool} . This allows us to estimate how long it has been since the last mass transfer phase, which also tells us if the luminous star is likely to be out of thermal equilibrium (i.e. if its thermal timescale is longer than the WD cooling age). The WD cooling age is particularly important for properly understanding the evolution of the shortest period systems, where additional angular momentum loss may have significantly altered their orbital period from what it was after the last mass transfer phase. It is important to correct for this effect when reconstructing their evolution (e.g. Zorotovic et al., 2010). There is degeneracy in reconstructing the past of a star by this method - whilst the mass of the WD provides the core mass of the progenitor star at the time of CE, it is likely that multiple models are able to reproduce a WD of a given mass, as we do not know in what stage of evolution the star was in at the onset of the CE.

In order to obtain the $T_{\text{eff,WD}}$, $\log(g)_{\text{WD}}$ and τ_{cool} , we matched our de-reddened *FUV* values (obtained by taking the *FUV* magnitude from *GALEX* and de-reddening by our calculated reddening values) and our WD mass values against interpolated values from models. For WDs with a mass measured below $0.5 M_{\odot}$ we used the helium core models of Althaus et al. (2013)⁷, whilst for more massive WDs (above $0.5 M_{\odot}$) we used the DA Carbon-Oxygen (CO) core models of Bédard et al. (2020)⁸, assuming a standard mass-radius relationship. We use best fit reddening for simplicity, though this may be slightly less reliable for the more distant objects of LAMOST. Note that, as our spectroscopic masses are only lower limit estimates, this likewise puts a lower limit on our $T_{\text{eff,WD}}$ values (since if the WD has a higher mass, hence a smaller radius, its temperature must increase to match the UV flux). Since some of our spectroscopic systems have minimum WD masses below $0.2 M_{\odot}$ we are not able to get temperature estimates for all our

⁷<http://evolgroup.fcaglp.unlp.edu.ar/TRACKS/newtables.html>

⁸<https://www.astro.umontreal.ca/~bergeron/CoolingModels/>

systems.

With our stellar and binary parameters established, we can compare our values to those found by other means to check the integrity of our method, and investigate the implications of what our parameters tell us about the evolution of these systems.

Based on our $T_{\text{eff,WD}}$ values, we can estimate the WD flux contributions in various passbands. We find that in the u band for example the vast majority of WDs contribute less than 5 per cent of the observed flux, and in most cases less than 1 per cent. This is true in the G band, which *Gaia* uses for astrometric measurements, and is therefore relevant to equation 3.6, in particular $\mathcal{S}$, the ratio of intensities. However, even accounting for a worst case scenario of a 5 per cent contribution in the G band ($\mathcal{S} = 0.05$), the resulting increase in M_{WD} is smaller than the uncertainties from our method.

3.4 HST Observations

Eight of our systems have been observed spectroscopically at UV wavelengths with the *HST*. These data allow us to confirm the origin of the UV excess in these objects and in the cases where this is due to a WD, we can determine their physical parameters by fitting the spectrum. Here we present *HST* data for four new objects comprising three WD + FGK binaries and an active star (TYC 6086-1317-1, TYC 9151-303-1, TYC 6434-457-1 and CPD-82 849), and refer the reader to previous publications for the other four objects (see section 3.5.1), though a breakdown of all eight systems is given briefly in Table 3.2.

Table 3.2: The eight systems within our sample which have *HST* UV spectra, with the Cosmic Origins Spectrograph (COS) using the G130M grating centred on 1291 Å and the Space Telescope Imaging Spectrograph (STIS) using the Multi-Anode Microchannel Array (MAMA) detector and the G140L grating centred on 1425 Å. Listed are the proposed source of their UV excess, the compiled exposure time and the source of publication.

Name	UV Source	Observation date	Exposure time [s]	Source
TYC 9151-303-1	WD in binary	2015 / 07 / 14	2441	This paper
CPD-82 849	Active star	2021 / 04 / 05	8718	This paper
TYC 6086-1317-1	WD in binary	2021 / 03 / 01	2196	This paper
TYC 6434-457-1	WD in binary	2020 / 12 / 31	4934	This paper
2MASS J06281844-7621467	Active star	2021 / 04 / 21	11731	Lagos et al. (2022)
TYC 7218-934-1	WD companion to a MS + MS binary	2015 / 04 / 29	4384	Lagos et al. (2020a)
TYC 6996-449-1	WD companion to a MS + MS binary	2014 / 12 / 03	2418	Lagos et al. (2022)
TYC 6992-827-1	WD in binary	2022 / 01 / 10	4980	Parsons et al. (2023)

For the four *HST* spectra clearly containing a WD we fitted synthetic DA WD models in order to determine the stellar parameters. We followed the procedure outlined in Parsons et al. (2023), whereby we used a pre-generated model grid created using the code of Koester (2010), spanning a range of effective temperatures of 12000–30000 K in steps of 200 K and surface gravities of 6.0–9.0 in steps of 0.1 dex, and interpolate between these grid points. Additionally, we included the effects of reddening and interstellar neutral hydrogen (although the latter has a very minor effect) and scale the model flux based on parallax. Thus the free parameters were effective temperature, surface gravity, parallax and reddening. WD masses, radii and cooling ages are then determined via a theoretical mass-radius relationship (Bédard et al. 2020 for masses above $0.5 M_{\odot}$ or Althaus et al. 2013 for masses below $0.5 M_{\odot}$).

We used the MCMC method to fit the spectra, implemented using the ensemble sampler EMCEE (Foreman-Mackey et al., 2013), with 4000 steps and 100 walkers, where the autocorrelation time for each parameter was generally found to be less than 100 steps, and a burn-in period of 5 times that of the autocorrelation time was used. We applied Gaussian priors to the parallax and reddening based on measurements from *Gaia* and the 3D reddening map of STILISM (Capitanio et al., 2017), respectively. We also add in quadrature systematic errors of 1.5 per cent in T_{eff} and 0.04 dex in $\log(g)$ (Parsons et al., 2023). For the astrometric binary systems we also generated model spectra based on the dynamically determined WD parameters.

3.5 Discussion

3.5.1 Comparison of dynamical WD masses to spectroscopic masses from HST UV spectroscopy

Of the eight systems previously mentioned to have been observed with *HST* spectroscopy, four (2MASS J06281844-7621467, TYC 7218-934-1, TYC 6996-449-1 and CPD-82 849) were identified as contaminants, with CPD-82 849 having not yet been published. Its UV spectrum (as seen in Figure 3.2) clearly identifies it as an active star.

The other four systems with *HST* spectra - TYC 6992-827-1, TYC 6086-1317-1, TYC 9151-303-1 and TYC 6434-457-1 - clearly contain a WD, with the best-fit parameters shown in Table 3.3, and are each discussed in more detail below. For the following discussion we refer to the parameters measured via the *Gaia* orbital solution plus *GALEX/FUV* fit as “dynamical” measurements, while those measured via fitting the *HST* UV spectrum are referred to as "spectroscopic" measurements. It is also worth noting that TYC 9151-303-1 was flagged by our SED fitting method as a contaminant, with the two-star model SED fitting the system better - which could indicate either that our SED contamination detection method may not always be reliable or that the SED is genuinely contaminated, either by a background source or a distant companion to the binary.

TYC 6992-827-1

Despite the large difference in mass between our dynamical mass and that of Parsons et al. (2023) shown in Table 3.3, it should be noted that this system is a spectroscopic binary, and thus this is only a minimum mass estimate. If we are to apply the inclination of $26 \pm 2^\circ$ from Parsons et al. (2023), we instead get a mass of $0.30 \pm 0.02 M_\odot$, which is consistent with their value, and is illustrated in Figure 3.3. This is unsurprising given

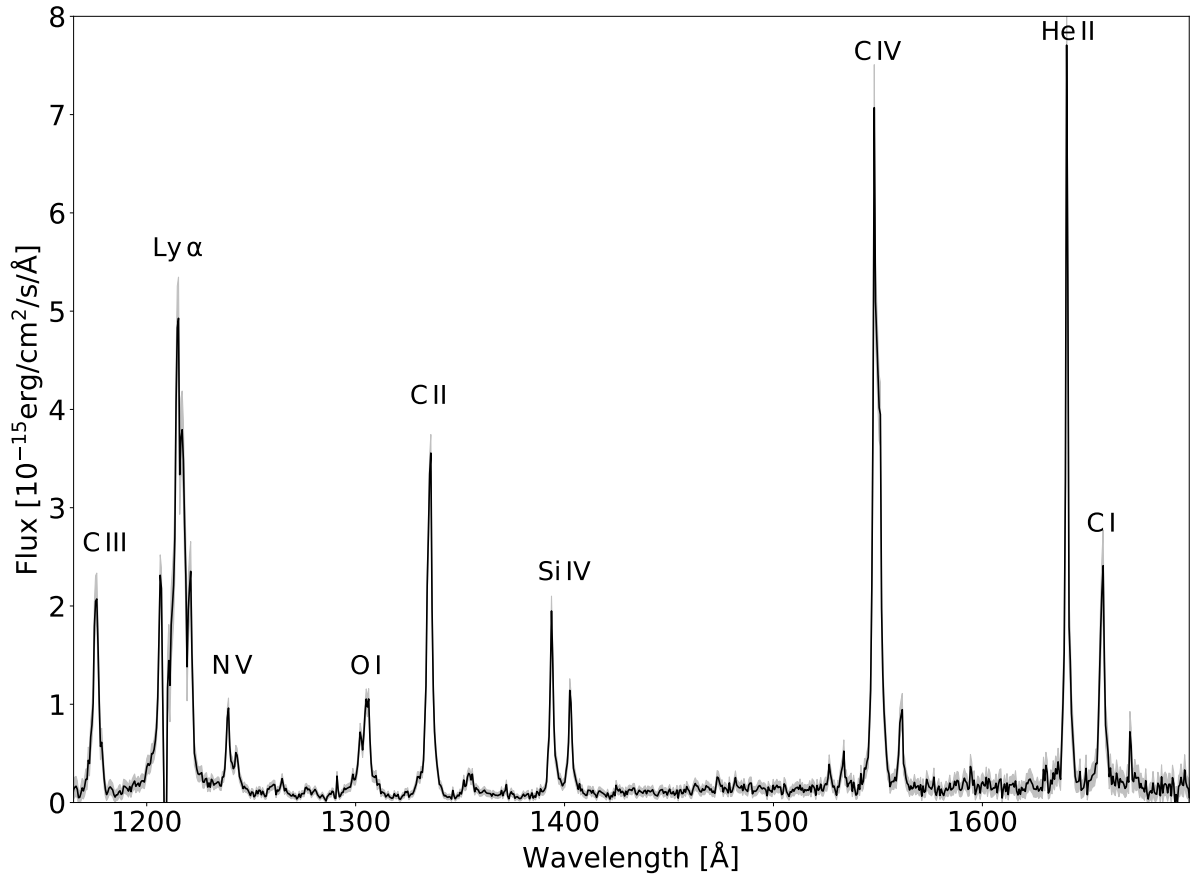


Figure 3.2: The *HST*/*STIS* spectrum of CPD-82 849. The spectrum lacks any clear indication of a WD, but does show strong emission lines typically seen in active stars, which are likely the origin of the UV excess in this system.

Table 3.3: A comparison of the WD parameters found through orbital analysis and SED fitting of *Gaia* data (“dynamical”) against those from fitting *HST* UV spectra (“spectroscopic”). The analysis of the UV spectrum of TYC 6992-827-1 was presented in Parsons et al. (2023) and we list their values here. Both TYC 6992-827-1 and TYC 6434-457-1 are spectroscopic binaries, hence the dynamical constraints represent lower limits (i.e. assuming $\sin(i) = 1$), which for TYC 6992-827-1 gives a WD mass so low that we are unable to estimate its temperature or surface gravity. The two methods give consistent results to within 2-3 σ in all cases.

Name	P_{orb} [d]	Method	$T_{\text{eff,WD}}$ [K]	$\log(g)_{\text{WD}}$ [dex]	τ_{cool} [Myr]
TYC 6992-827-1	41.45 ± 0.01	Dynamical Parsons et al. (2023)	- 15750 ± 50	- 7.14 ± 0.02	- 6.9 ± 0.1
TYC 6086-1317-1	524.2 ± 3.3	Dynamical	20100 ± 400	7.29 ± 0.04	40 ± 6
		Spectroscopic	19850 ± 350	7.12 ± 0.05	20 ± 12
TYC 9151-303-1	797.8 ± 9.6	Dynamical	15700 ± 300	7.51 ± 0.03	190 ± 13
		Spectroscopic	14900 ± 250	7.35 ± 0.06	184 ± 26
TYC 6434-457-1	930.2 ± 9.8	Dynamical	$>14800 \pm 1500$	$>7.78 \pm 0.12$	$>234 \pm 26$
		Spectroscopic	13600 ± 300	7.93 ± 0.12	252 ± 23

that the *Gaia* orbital fit is consistent with the ground-based one presented in Parsons et al. (2023).

TYC 6086-1317-1

TYC 6086-1317-1 was flagged as an astrometric binary system by *Gaia*, and so its mass estimates are more accurate, since the inclination is known. The dynamical and spectroscopic WD parameters are consistent to within 2-3 σ demonstrating that the dynamical method can give reliable results. To further highlight this, the *HST* spectrum of this system is shown in the top panel of Figure 3.4 with both the best fit model spectrum and a model spectrum computed at the dynamically determined WD parameters. Both methods indicate the WD has a low mass and very short cooling age (see Table 3.3).

TYC 9151-303-1

TYC 9151-303-1 was flagged as an astrometric binary system by *Gaia*. Just as with TYC 6086-1317-1 the dynamical and spectroscopic parameters are consistent to within

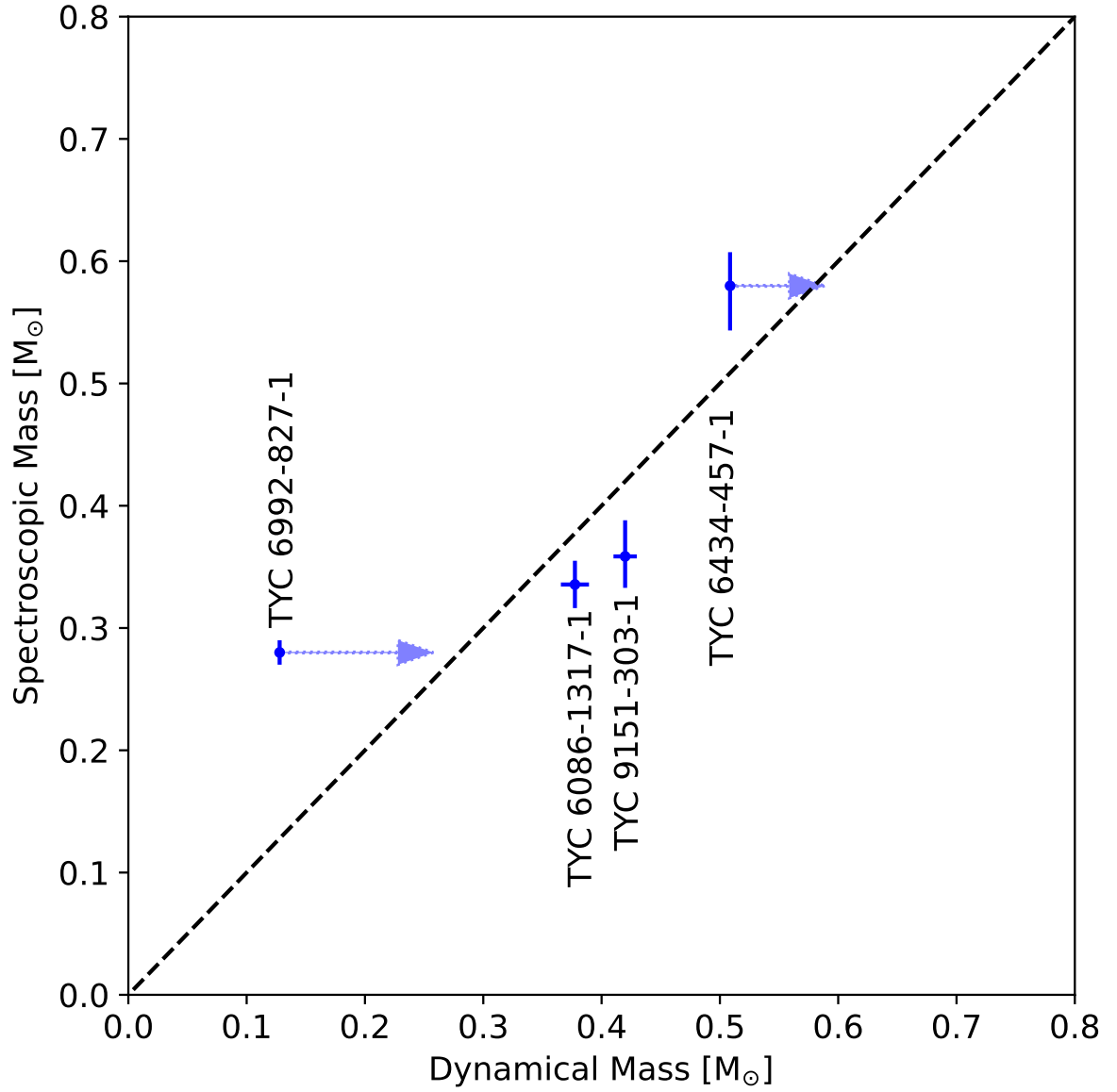


Figure 3.3: A comparison of the dynamical WD mass from *Gaia* orbits (x-axis) vs those found through *HST* spectral fitting (y-axis).

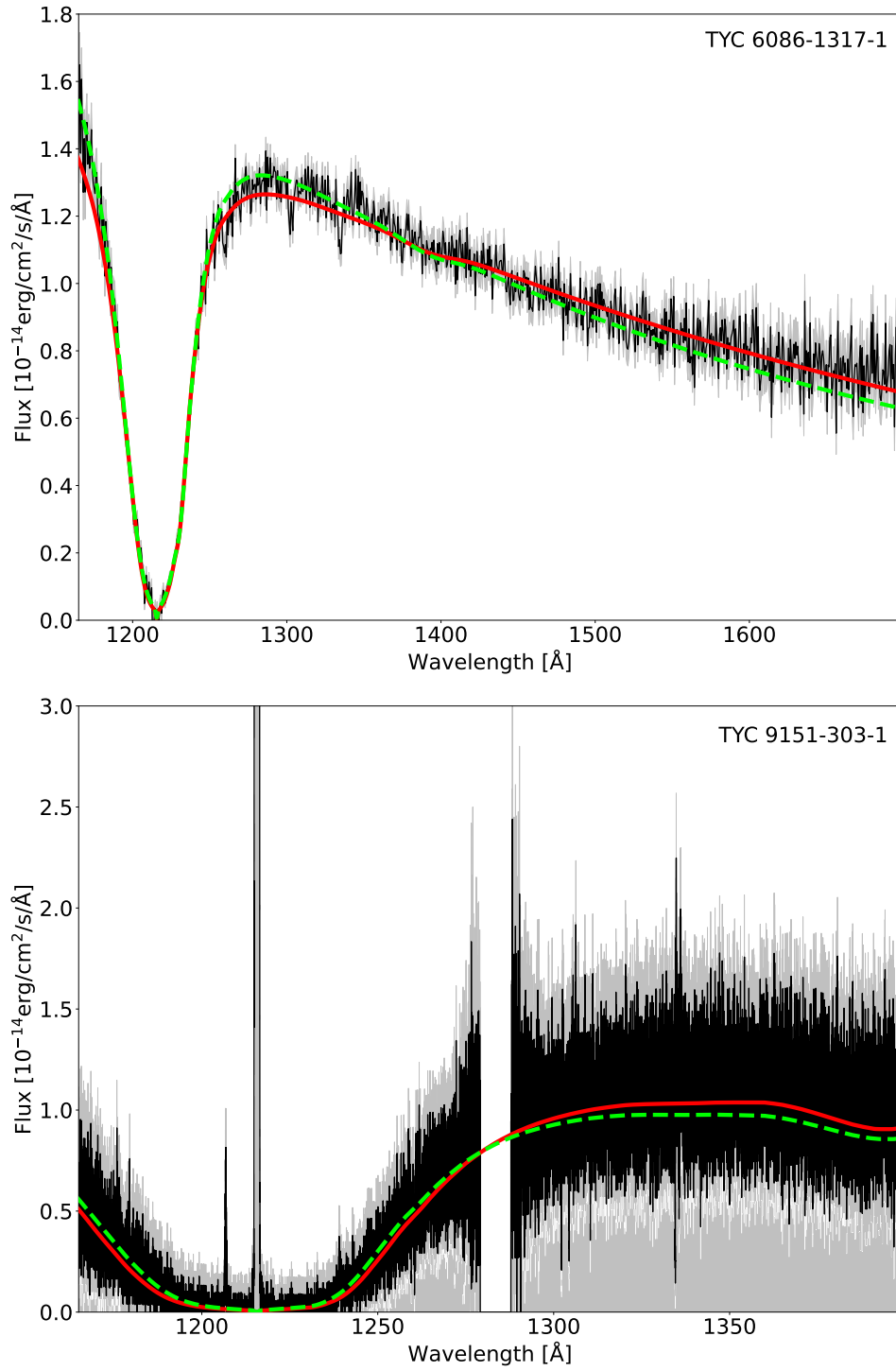


Figure 3.4: UV spectra of the astrometric binary systems TYC 6086-1317-1 (top, STIS) and TYC 9151-303-1 (bottom, COS). Overplotted are the best fit models in red, while models with the parameters fixed at the “dynamical” values are shown as green dashed lines.

2-3 σ . This system also contains a low mass WD, albeit with a slightly longer cooling age than TYC 6086-1317-1. The UV spectrum of this source is shown in the bottom panel of Figure 3.4.

TYC 6434-457-1

TYC 6434-457-1 is a single-lined spectroscopic binary in *Gaia*, which has an orbital period comparable to many of the astrometric binary systems. Assuming an edge-on orbit gives a minimum mass for the WD of $0.50 \pm 0.06 M_{\odot}$, which is somewhat lower than the spectroscopically determined mass of $0.58 \pm 0.03 M_{\odot}$, implying that the system has an inclination of around 60 degrees. In contrast to the two previous objects, TYC 6434-457-1 appears to host a fairly typical mass WD. The *HST* spectrum of this object is shown in Figure 3.5.

3.5.2 Comparing to previous works

Each of the three surveys of Parsons et al. (2016), Rebassa-Mansergas et al. (2017) and Ren et al. (2020) calculated specific stellar parameters for the luminous companion, with which we can compare our values against. Given that the dynamical WD masses are entirely dependent on the masses of the luminous stars, it is vital that these values are as reliable as possible. Parsons et al. (2016) and Rebassa-Mansergas et al. (2017) each determined values of $T_{\text{eff,LS}}$ and $\log(g)_{\text{LS}}$, whilst Ren et al. (2020) measured values for $T_{\text{eff,LS}}$ and R_{LS} , the comparison of these values to those found by our dynamical modelling can be observed in Figure 3.6.

RAVE and LAMOST

We find that, compared to the values of Parsons et al. (2016) and Rebassa-Mansergas et al. (2017), our temperatures were mostly consistent.

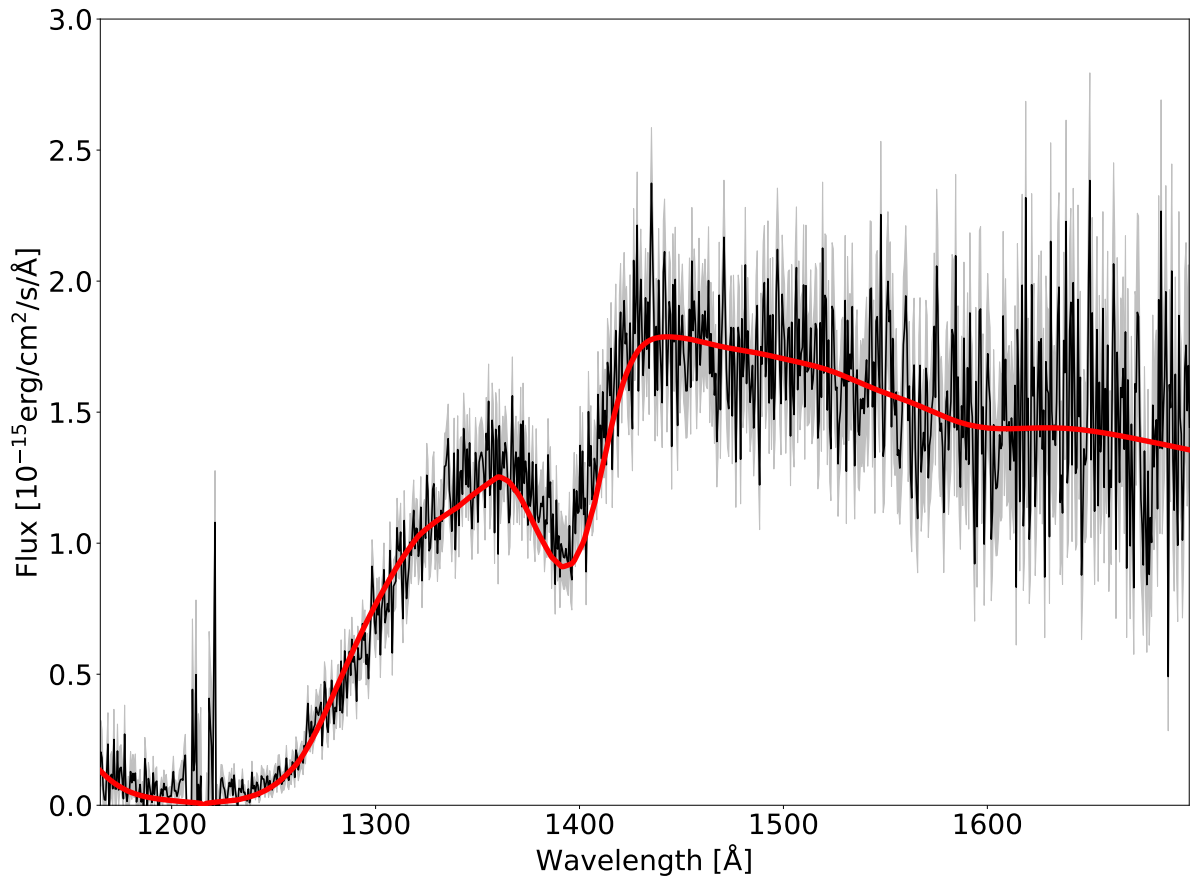


Figure 3.5: The *HST/STIS* spectrum of the spectroscopic binary system TYC 6434-457-1. The best fit model spectrum is shown in red, we do not plot a model based on the “dynamical” measurements, since this assumes an edge-on orbit and hence underpredicts the WD mass.

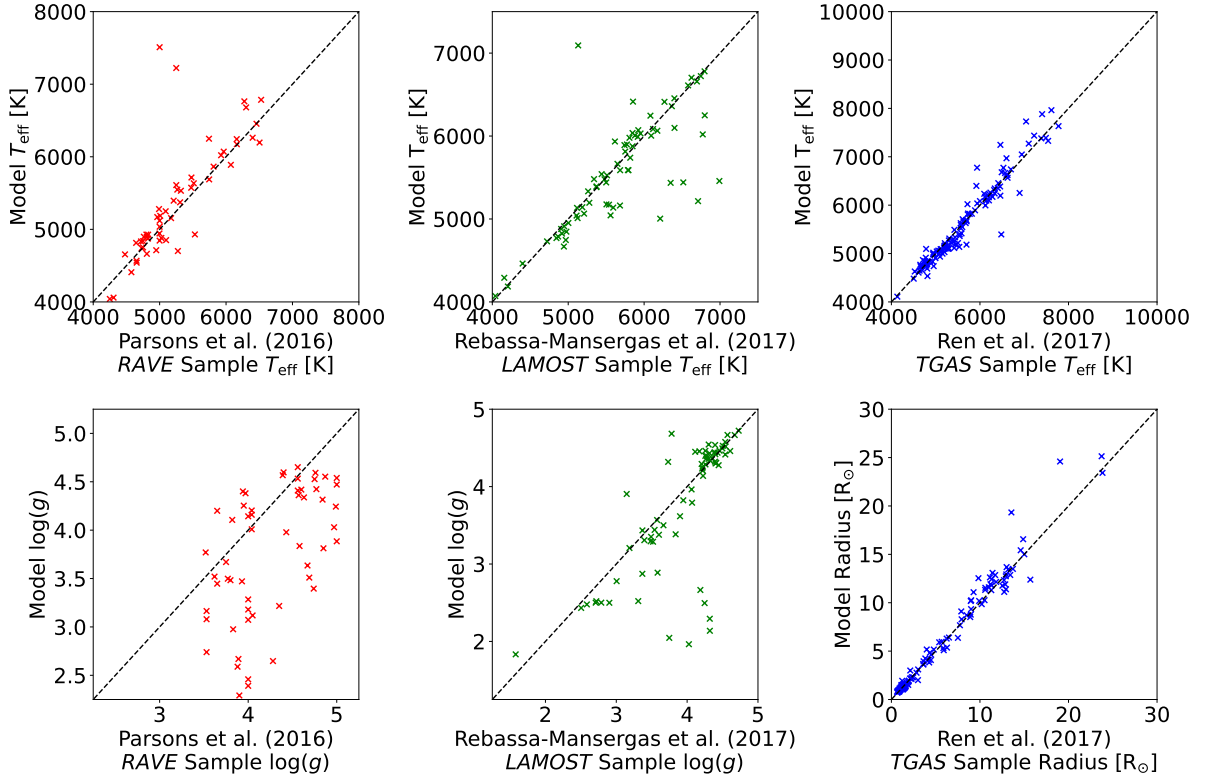


Figure 3.6: A comparison of our parameters against those of Parsons et al. (2016), Rebassa-Mansergas et al. (2017) and Ren et al. (2020). Note that for Parsons et al. (2016) and Rebassa-Mansergas et al. (2017) these were made before any *Gaia* Data Release (DR), hence the miss-identification of many evolved stars in those studies.

The comparison of our values of $\log(g)_{\text{LS}}$ is quite telling. There are many systems across both surveys (particularly those of *RAVE*) in which our values were considerably lower than those found by either Parsons et al. (2016) or Rebassa-Mansergas et al. (2017), which is consistent with our earlier discovery of giant stars in their samples which they had identified as MS stars.

TGAS

Both the temperatures and stellar radii from the survey of Ren et al. (2020) match very closely with the values we found. This is unsurprising, as Ren et al. (2020) likewise obtained their values through SED fitting, though they used parallaxes from *Gaia* DR2, whilst we used the updated versions from *Gaia* DR3.

3.5.3 Comparing luminous star masses with *Gaia*

Another useful source to compare against is the `gaiadr3.binary_masses` catalogue, which contains mass estimates for many systems which *Gaia* has flagged as being binaries. We should note that, of our sample of 246 systems, only 124 had a mass estimates in the *Gaia* binary masses table, as *Gaia* seemingly does not generate parameters for such systems where the optically luminous companion has evolved off the main sequence. Given that this is a crucial parameter to determine the WD mass, there is a clear need to derive these ourselves or WD masses would not be constrained for a significant fraction of our sample. In general, our masses show good agreement with the *Gaia* values, as can be observed in Figure 3.7, with the more extreme outliers being systems which we have flagged as contaminants.

It should be noted that, of the systems absent from the `gaiadr3.binary_masses` catalogue, all except 2 can be found as more evolved stars along the giant branch. When using the *Gaia* binary masses table one should be aware of this bias.

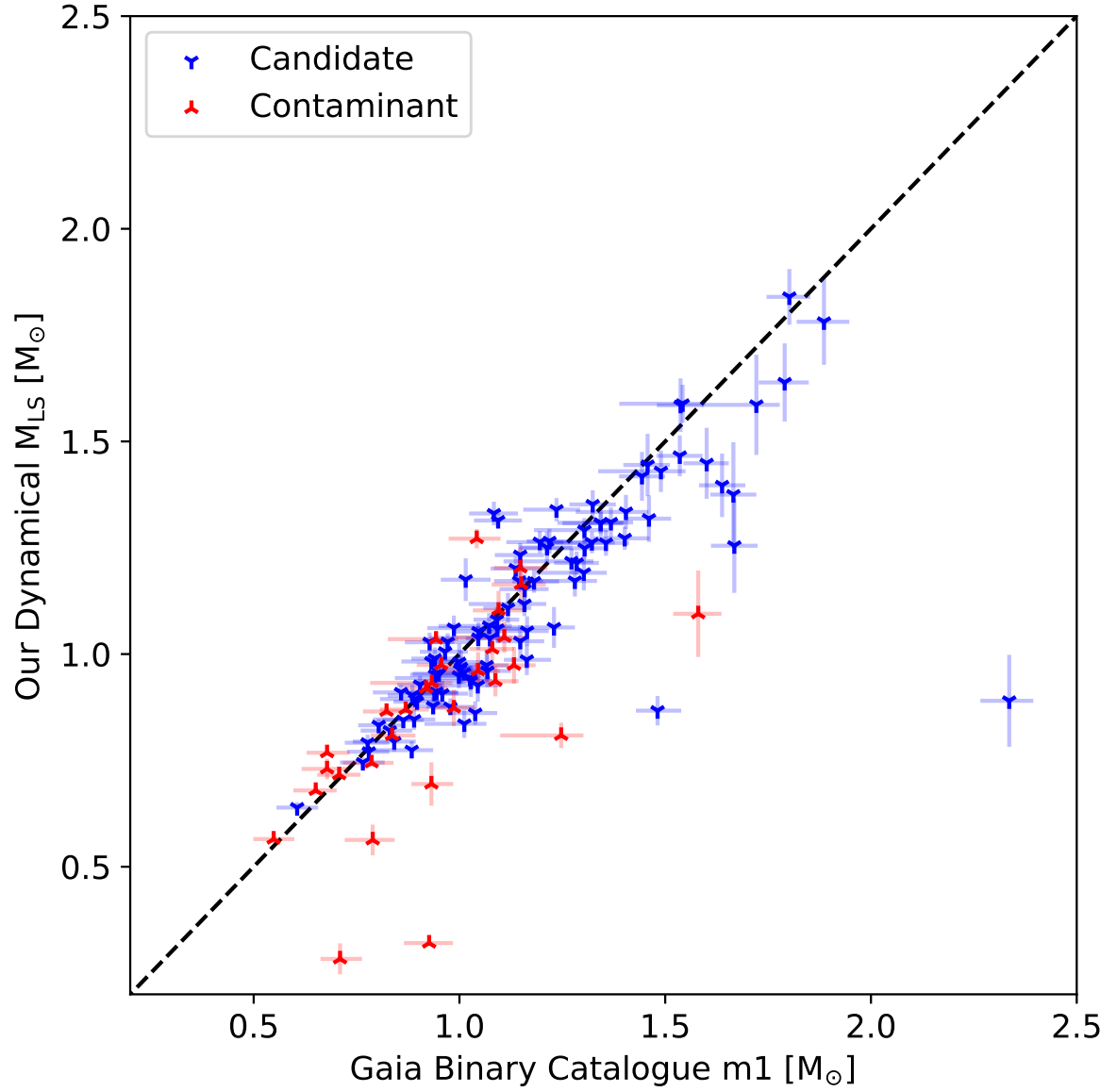


Figure 3.7: A comparison between our dynamical masses of the more luminous companion against their respective masses found in the `gaiadr3.binary_masses` catalogue. Only around 50 per cent of our sample had masses in the *Gaia* catalogue, with evolved stars missing from *Gaia*.

3.5.4 Evolutionary states

In Figure 3.8, we show the orbital period vs the WD mass distribution, with two panels - one each for the more robust astrometric data, and for the lower mass estimates from the spectroscopic data. As can be observed, we have a wide range of orbital periods from our candidate systems. We can see that for our astrometric binaries (top panel) our systems lie near the region for post-SMT systems as proposed by Rappaport et al. (1995) (the grey shaded region), with few outliers. A similar result was recently presented by Shahaf et al. (2024) using a purely astrometrically-selected sample of systems. We note that this relation is based on donor stars on the RGB, which appears to be the case for many of our systems where the WD mass is $< 0.5 M_{\odot}$, but this evolutionary channel may not be able to explain the origin of systems with higher mass WDs that likely reached the AGB. A small but significant number of our systems sit just below the SMT region, with similar parameters to the self-lensing systems discovered by the *Kepler* mission (Kruse & Agol, 2014b; Kawahara et al., 2018). Given their long periods it is still challenging to explain them as a result of CEE, even assuming very efficient envelope removal. Interestingly, the luminous star in many of these systems is somewhat evolved itself, generally on the subgiant branch. This is unsurprising if these systems are the result of SMT, since this requires an initial mass ratio close to unity and therefore similar main-sequence lifetimes for the two components. Given their current stellar and binary parameters these systems are likely to undergo a CE phase at some point in the future. Should both components survive this additional mass transfer phase, this would lead to the creation of a double WD binary, and could represent a significant formation channel for such systems.

The spectroscopically identified systems (bottom panel of Figure 3.8) show much wider distributions for both period and WD mass. Given that we only have lower limits on the WD masses the picture is less clear for these systems. There are some clear post-CE systems with periods less than a couple of weeks and minimum WD masses

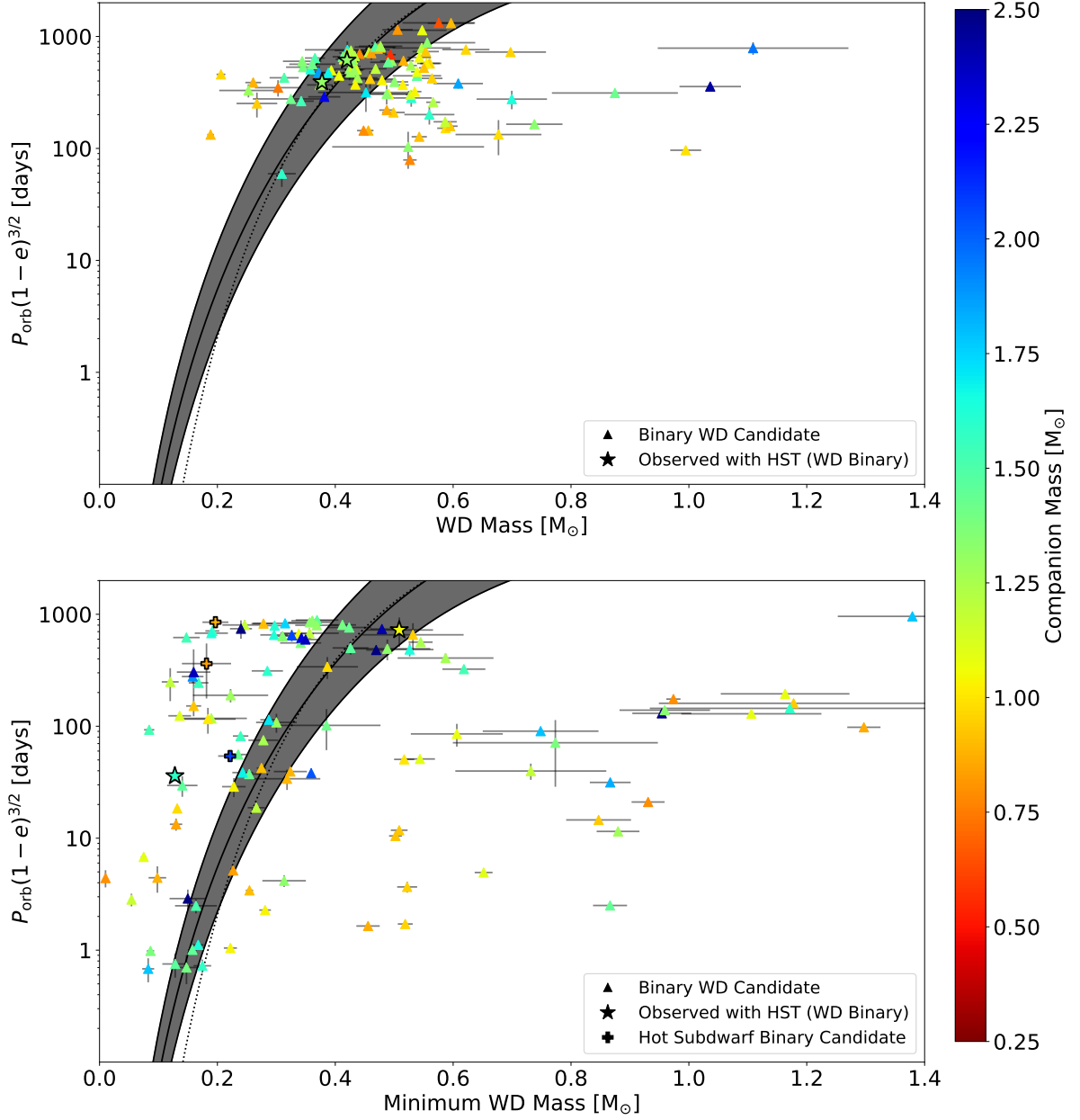


Figure 3.8: M_{WD}/P relationships for our candidate WD binary systems, colour-coded by the mass of the luminous companion, and split by their solution type (top panel: astrometrically detected systems, bottom panel: spectroscopically detected systems). Of note, the WD mass is only a minimum mass estimate for the spectroscopic systems. The solid black line and shaded grey region represent the theoretical region for conservative post-SMT binaries from Rappaport et al. (1995), with the dotted line representing an update on this from Lin et al. (2011). Systems above this region may be explained by non-conservative SMT.

around $0.5 M_{\odot}$, similar to other systems found in *The White Dwarf Binary Pathways Survey*. However, there is a significant number of systems with very low minimum WD masses, covering a wide range of periods. While these could all be low inclination post-CE systems, there is also a possibility that there is a population of post-SMT systems ranging from periods of a day up to 1000 d. Indeed the shortest periods systems, EL CVn binaries, are already known and intermediate period post-SMT binaries have now also been found (Parsons et al., 2023). Given the low WD masses, these may well be the progenitors of double WD systems containing at least one extremely low mass WD.

We also note that there are a number of systems in both the astrometric and spectroscopic samples with clearly high mass WDs and orbital periods longer than a few weeks. The high WD masses make these systems challenging to explain as the result of SMT, but equally their long orbital periods are challenging to explain via standard CEE. Recently Yamaguchi et al. (2024a) discovered 5 such systems occupying this parameter space (albeit with slightly shorter orbital periods than many of our systems) which, combined with the roughly 25 such systems we find, clearly indicates that there is a population of WD binaries in this region of parameter space. Yamaguchi et al. (2024a) proposed that these systems could be the result of CEE if internal (recombination) energy also aids the expulsion of the envelope. Whether this can also explain the systems we find with orbital periods of 100s of days is unclear.

One clear result appears to be that a far wider range of periods is viable for WD + FGK systems compared to WD + dM binaries, which generally have periods averaging around 10.3 hours (Nebot Gómez-Morán et al., 2011), with a very small sample of WD + dM binaries from Shahaf et al. (2024) having relatively long periods being the current major exception, whilst WD + FGK systems can span periods from around half a day to almost 1000 d. This is likely a result of the multiple different formation pathways possible for WD + FGK systems, whereas the extreme initial mass ratios of WD + dM systems mean that they are all likely the result of standard CEE.

3.5.5 Systems with candidate hot subdwarf stars

We made a somewhat empirical cut to determine if the system was a hot subdwarf candidate, by flagging systems with an absolute *FUV* magnitude brighter than 5.2 mag as being hot subdwarf binary candidate systems, opposed to WD binary systems. Doing so, we have found three systems in our sample that are candidate hot subdwarf binaries, as can be observed in Figure 3.1, given their extreme UV luminosities. Hot subdwarf stars are core helium burning stars that have been stripped of their envelope (Heber, 2009), with masses in the domain of $\sim 0.4\text{--}0.5 M_{\odot}$ (Vos et al., 2018), and are bright in the ultraviolet, similar to WDs - though they are brighter at optically blue wavelengths in comparison. This means that the cut to remove systems a magnitude bluer than the main sequence track made in Parsons et al. (2016), Rebassa-Mansergas et al. (2017), Ren et al. (2020) and our present study should remove such systems in a binary with a dwarf late F, G or K companion. However, such a cut would not remove hot subdwarfs with a more evolved, hence luminous companion, as a similar cut was not made along the giant branch. Hot subdwarf binaries typically come in two groups; those with low mass companions in short period systems (such as those discussed in Kupfer et al. 2015), and those with higher mass companions and a longer orbital period (as discussed in Vos et al. 2018).

Our three hot subdwarf candidates are in binaries with evolved companions (see Figure 3.1), and are found spectroscopically. Two of our three systems, UCAC2 15655859 and TYC 4889-1238-1, possess periods that are consistent with the established period domain of hot subdwarfs with FGK stars from Vos et al. (2018) (having periods of ~ 996 and 1079 d respectively, and minimum masses of $\sim 0.19 M_{\odot}$). The third candidate, TYC 6472-1267-1, has a period of around 56 d, which is unusual, as there is a dearth of hot subdwarf binary systems with such periods (ignoring the systems with WD companions, which have passed through two mass transfer phases and so are not directly

comparable). It is worth noting that this system is a candidate triple system based on the findings of [Tian et al. \(2020\)](#), who flagged the system as potentially having a common proper motion companion. If true (which is somewhat dubious given the separation of 155302 au found by [Tian et al. 2020](#)), then this would be consistent with the findings of [Lagos et al. \(2020b\)](#) and [Parsons et al. \(2023\)](#), that these intermediate period post-SMT systems are generally found in triples, since they need to have very short initial separations for the WD to remain a low mass, as mass transfer must have begun before the progenitor to have accumulated much core mass. We do note however, that extremely low mass WDs can also have similar UV luminosities to hot subdwarf stars, so, while these are clearly not standard mass WDs, they may not be hot subdwarf stars either and follow up data are required to properly classify these objects.

3.5.6 UV Parameter Space

Given that both the *RAVE* and *LAMOST* samples were created before any *Gaia* DRs, it is useful to see where these systems sit in a UV colour-magnitude diagram, both the genuine WD + FGK systems as well as the contaminants. This may aid future selections of these kinds of objects. Figure 3.9 shows such a UV colour-magnitude diagram, separated by the systems found by [Parsons et al. \(2016\)](#), [Rebassa-Mansergas et al. \(2017\)](#) and [Ren et al. \(2020\)](#).

Most systems sit between the WD and MS track as expected for these kinds of objects. In general, there is more contamination towards fainter objects, with almost all sources fainter than $M_{FUV} \sim 15$ mag seen to be contaminants, likely active stars. However, there are also brighter contaminants that sit right in the main population of WD + FGK systems, including some that we have observed with *HST*, confirming that they are indeed contaminants. In general, these tend to be triple systems where the WD is a wide companion to a main-sequence binary. We also note that there appears

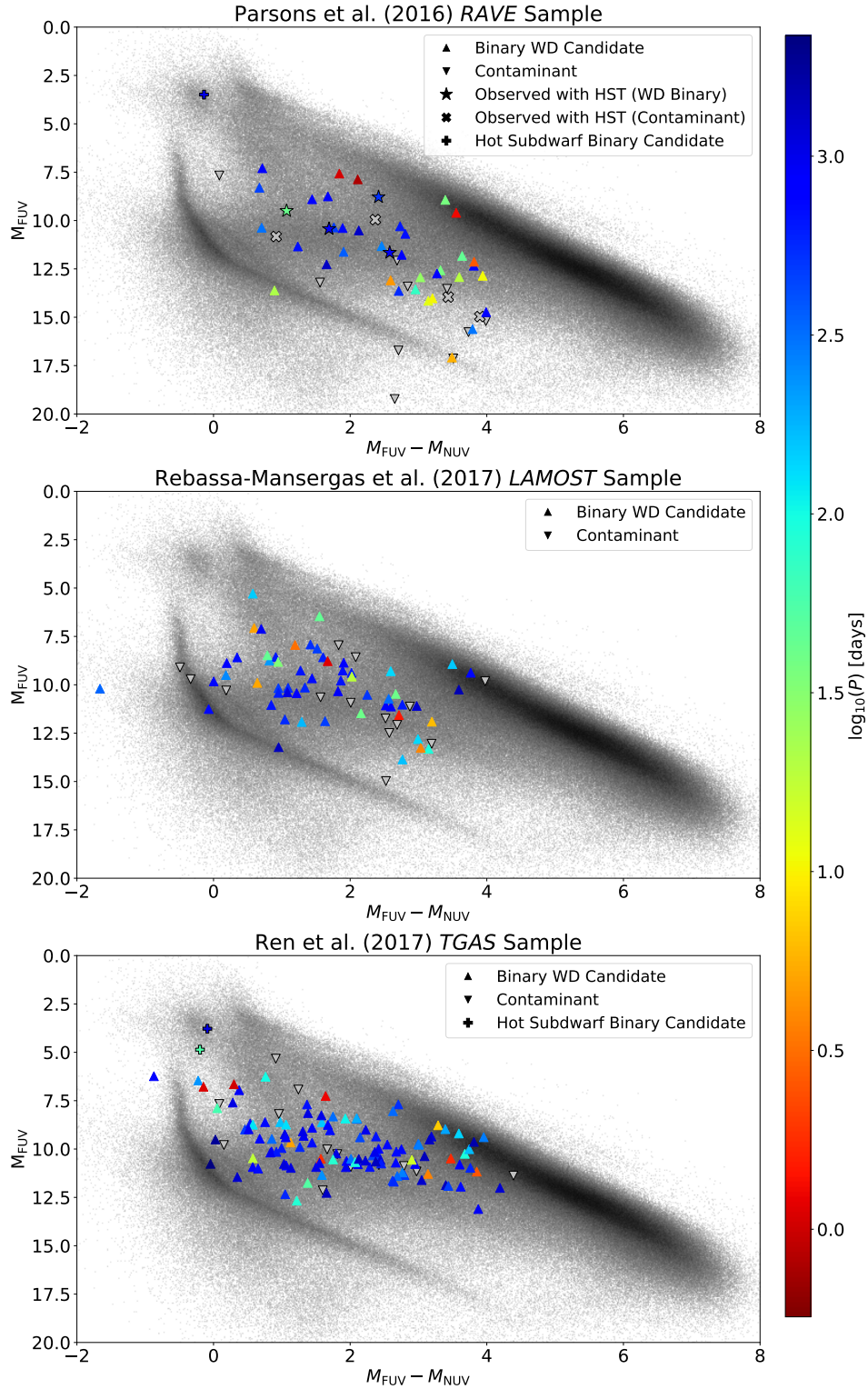


Figure 3.9: UV colour-magnitude diagrams using *GALEX FUV* and Near Ultraviolet (*NUV*) magnitudes, split by the three surveys of Parsons et al. (2016), Rebassa-Mansergas et al. (2017) and Ren et al. (2020). The points are colour-coded by the $\log_{10}$ of their period. A random sample of stars within 250 pc are shown in the background.

to be some genuine WD + FGK systems that show very minor UV excesses (those that sit close to the MS), which are likely systems containing cool and/or high mass WDs. However, there is also significant contamination close to the MS, so caution is needed when searching for WD binaries in this region.

We note that the largest source of contamination is generally due to active stars, i.e. binaries consisting of an FGK star plus a lower mass companion, where either one or both components have strong chromospheric emission in the UV. Despite this, we advise against removing active stars from catalogues before searching for UV excess systems, because many genuine WD + FGK systems contain an active FGK star, since they are often spun up as a result of mass transfer and/or tidal locking.

In addition to UV parameter space, we also looked into UV-optical parameter space, but found it unhelpful in comparison to the UV or Optical parameter spaces.

3.5.7 Astrometric Parameter Space

It is now possible to identify WD + FGK systems directly as astrometric binaries without the need for any UV data, by means of their astrometric mass function, $\mathcal{A}$, as described in Shahaf et al. (2019), and removing systems likely to be either a MS + MS or a hierarchical triple system. Shahaf et al. (2024) recently used this technique to identify several thousand candidate WD + FGK systems in *Gaia*. Given that our selection criteria are significantly different to theirs it is worth comparing the two methods. In particular, in Figure 3.10 we plot the astrometric mass function for our sample and indicate the typical region that a WD + FGK system is likely to reside. The Shahaf et al. (2024) method relies on ruling out the possibility of a binary being composed of either two luminous stars, or the companion being a binary itself (i.e. a triple system), which generally requires placing a fairly tight limit of $\mathcal{A}$ greater than around 0.4 (see Shahaf et al. 2024 for the exact cut). Applying the same cut to our samples would exclude a significant

fraction of all our systems. This is due to a combination of many of our WD masses being significantly lower than the canonical WD mass (possibly as a result of SMT) and our sample containing a large number of more massive luminous stars, since the Shahaf et al. (2024) sample cuts off at around $1.3 M_{\odot}$, where contamination from normal binaries overwhelms the WD systems. Many of our luminous stars are also giants, which were not included in the Shahaf et al. (2024) sample. Therefore, the UV-excess method appears to be the only way to identify systems with very low mass WDs and/or higher mass luminous stars at present. We do note that some of our systems sit quite outside the region expected for WD companions (i.e. the purple region in Figure 3.10) and while some of these objects have been identified as contaminants, it is possible that our candidates significantly above and below the WD companion region may also not be genuine WD + FGK systems.

As one could imagine, our sample is biased towards systems with a large UV excess - namely hotter, lower mass WDs, whilst our cut removing systems bluer than the main sequence as discussed in Section 3.2 is biased against lower mass luminous companions where the WD may contribute a significant percentage of the optical flux. There are further more complex selection effects in each of the parent samples contributing to our sample, see Parsons et al. (2016), Rebassa-Mansergas et al. (2017) and Ren et al. (2020) for more information on each. However, our bias towards hot, low mass WDs is complementary to the selection effects of the purely astrometric method of Shahaf et al. (2024), which is somewhat biased towards higher mass WDs, so a combination of both methods could lead to a more complete sample.

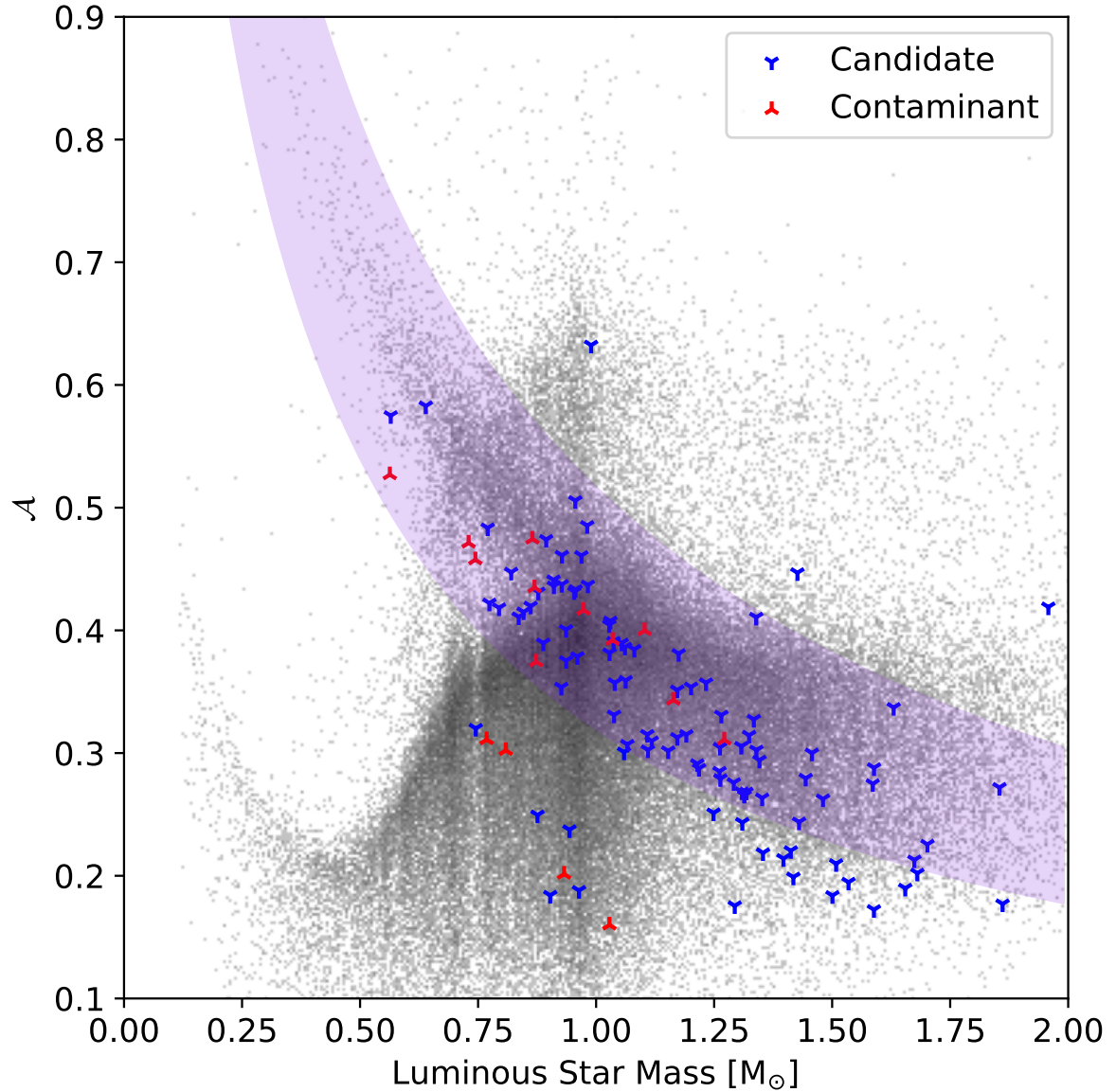


Figure 3.10: The relationship between the astrometric mass function of [Shahaf et al. \(2019\)](#), $\mathcal{A}$, and the mass of the luminous companion. The purple highlighted region represents the region where the hidden companions mass is between $0.4\text{--}0.75\ M_{\odot}$, a typical mass range for WDs in these systems. The full sample of astrometric binaries in *Gaia* is shown in the background. The vertical stripes within the background data is owing to the selection function for astrometric binaries within *Gaia* DR3, with the dip towards lower masses is owing to the astrometric signal reducing for lower mass objects.

3.6 Conclusions

We have confirmed the binary nature of 246 candidate WD + FGK binaries from Parsons et al. (2016), Rebassa-Mansergas et al. (2017) and Ren et al. (2020) using data from *Gaia* and combined this with modelling the SED of the luminous star in order to constrain the mass of the unseen WD. Once systems which have been flagged as likely contaminants are set aside, we have a sample of 202 WD + FGK binary candidates, four of which have been confirmed through *HST* spectroscopic observations in the ultraviolet and one of which has been published before (Parsons et al., 2023).

We find that our astrometric systems occupy a region of parameter space that is incompatible with a post-CE origin, given their low WD masses, but they do lie near the relationship proposed by Rappaport et al. (1995) for post-SMT binaries, indicating these systems likely underwent a period of stable, non-conservative mass transfer earlier in their evolution. Many of these systems are likely to be the progenitors of double WD binaries.

The analysis of the spectroscopically identified systems is complicated by the fact that we can only set a lower limit on the WD parameters. Nevertheless, they confirm the existence of WD + FGK binaries at a wide range of orbital periods, from less than a day, to more than 1000 d, in contrast to the population of WD + dM binaries. We also identify a group of systems with orbital periods of more than a few weeks containing high mass WDs, which are difficult to reproduce either via SMT or standard $\alpha_{\text{CE}} \sim 0.3$ CEE.

Chapter 4

The *Gaia*-*GALEX* UV Excess

Sample for systems within 350 pc

“ It’s so very lonely,
you’re a thousand
light years from home ”

— The Rolling Stones, *2000 Light Years From Home*, 1967

Declaration: Part of the science in this chapter was done and written by a co-author. The initial crossmatch between *Gaia* Data Release (DR)3 and *Galaxy Evolution Explorer* (*GALEX*) was done by Dr. Nicola Gentile Fusillo. My contributions to the sample begin from applying the numbered cuts in Section 4.2.

Chapter Summary

White Dwarf (WD)s with an F, G or K type companion (or giant stars which evolved from such a companion) are the last common ancestor to a zoo of exotic phenomena (see Section 1.3.4). Finding a clean sample of such systems is difficult, as WDs in such binaries are usually outshone at optical wavelengths by their non-degenerate companion. It is useful to have a sample of these WD + FGK binaries, as they can be studied to investigate binary evolution - as these systems will have underwent a previous phase of mass transfer and can go on to become a host of interesting systems. Using both *Gaia* DR3 and *GALEX*, in this chapter we compile a sample of 2597 candidate WD + FGK binary systems within 350 pc. These were identified by their Ultraviolet (UV) excess compared to what MESA Isochrones & Stellar Tracks (MIST) models fitted with the systems *Gaia* stellar parameters predict, after we apply corrections to systematic uncertainties found in the UV predictions of said MIST models. We estimate the mass, surface gravity and effective temperature of the WD by fitting the excess UV flux to models, or through interpolation where there was only a clear excess in one UV band. We estimate the age of the system where possible by comparing against wide resolved WD companions, or by checking if the system is a known member of a cluster. By comparing against SIMBAD, we estimate the level of contamination within our sample, finding between 10-35 per cent contamination. The sample found here is valuable for investigation populations of hotter WDs, and of WDs with a giant star as a companion.

4.1 Introduction

WDs are the final stage of evolution for a star of initial mass of $\lesssim 9 M_{\odot}$ (Kepler et al., 2007; Cummings et al., 2018; Santos-García et al., 2025). 18-26 per cent of WDs are known to exist in binaries (Holberg, 2009; Toonen et al., 2017), meaning that the WD previously evolved alongside a companion. If the initial orbital period of this binary system was short enough, $P_{\text{orb}} \lesssim 10^4 \text{ d}$, then it is likely that the two stars will have interacted as the WD progenitor evolved (Willems, B. & Kolb, U., 2004). Systems consisting of a WD and an M Dwarf (dM) (WD + dM) are well studied (e.g. Rebassa-Mansergas et al. 2021), those which are close enough will go on to become cataclysmic variables, otherwise they will remain detached. More interesting are systems consisting of a WD with a more massive F, G or K spectral type star (WD + FGK), as these have a more variable past and future evolution which we can probe.

We expect that systems containing an intermediate to high mass WD, $M_{\text{WD}} \gtrsim 0.4 M_{\odot}$, with a shorter orbital period, $P_{\text{orb}} \lesssim 100 \text{ d}$, to be the result of a phase of Common Envelope Evolution (CEE) (Paczynski, 1976; Zorotovic et al., 2010). Such a phase is difficult to model through hydrodynamics, though it generally involves a period of spiralling-in as friction robs the system of orbital energy. This phase generally occurs as the progenitor of the WD evolves onto the Red Giant Branch (RGB) or onto the Asymptotic Giant Branch (AGB), where the radius of the star dramatically increases causing the outer envelope to swallow the companion. Low mass, helium core WDs are thought to form through this pathway, as the outer layers of the RGB star are stripped away leaving behind the helium core as a WD, while higher mass Carbon-Oxygen (CO) or even Oxygen-Neon (ONe) core WDs form during AGB interactions. An alternative method of interaction is Stable Mass Transfer (SMT), wherein the companion to the WD progenitor accretes mass overflowing from the progenitor at a steady rate, which can lead to a widening of the binary (Webbink, 2008; Podsiadlowski, 2014). Until *Gaia*

DR 3 (Gaia Collaboration et al., 2023b), the vast majority of WD + FGK binaries were short period systems of $\lesssim 2.5$ d (e.g. Parsons et al. 2015; Hernandez et al. 2020, 2022a; Lagos et al. 2022; Hernandez et al. 2022b). More recently, using *Gaia*, longer period ($\gtrsim 100$ d) WD + FGK binaries have been discovered (e.g. Shahaf et al. 2024; Garbutt et al. 2024).

There are three main methods for identifying WD + FGK binaries; astrometry (e.g. Shahaf et al. 2024; Yamaguchi et al. 2025), self-lensing (e.g. Maeder 1973; Kruse & Agol 2014b; Yamaguchi et al. 2024a) and by their UV excess (e.g. Parsons et al. 2016; Rebassa-Mansergas et al. 2017; Ren et al. 2020). In this paper, we will be using the latter method to create a sample of WD + FGK binaries using *Gaia* data for the non-degenerate companion, and using *GALEX* (Martin et al., 2005b) UV measurements to detect potential hidden WDs. Previous samples using this method lacked *Gaia* parallax measurements, and as such the parameters of the non-degenerate companion and of the binary system as a whole were thus less certain - and indeed subsequent observations of some of these systems (e.g. by Garbutt et al. 2024) were found to contain giant stars, when they were previously thought to be on the Main Sequence (MS). This may have caused some objects to be incorrectly flagged as having a UV excess or genuine UV excess systems to be missed. A downside of the UV excess method is that it does not provide orbital separations, meaning detached WD + FGK binaries that will have never interacted may be present in the resulting sample. This method also is more sensitive to younger WDs, as these are hotter and thus more luminous at UV wavelengths.

We set out to make a new sample using both *Gaia* data to identify the properties of the non-degenerate companion, and *GALEX* data to probe for UV excesses, so that we can compile a sample with more certain constraints on the stellar companion (particularly effective temperature (T_{eff}), radius (R), luminosity and metallicity), and thus a more accurate idea on if these systems have a genuine UV excess. We also determine correction

factors to apply to MIST ¹ isochrones Dotter (2016); Choi et al. (2016); Paxton et al. (2011, 2013, 2015) model predictions in the UV, to bring them into agreement with observations and hence make it easier to identify genuine UV excess objects.

¹<https://waps.cfa.harvard.edu/MIST/>

4.2 Target Selection

The first step in defining our sample was to build a reliable *Gaia*-*GALEX* cross-match to serve as the basis for candidate selection. We started from the 1.4677 billion *Gaia* DR3 sources with full astrometric solutions (i.e., measured parallax and proper motion) and cross-matched their J2016 coordinates with *GALEX* GR7. For each *Gaia* source, we retrieved all *GALEX* detections within 40".

To account for proper motion, we compared the modified Julian date (MJD) of each *GALEX* observation to *Gaia*'s reference epoch (J2016; MJD 57 388). Using this epoch difference, we propagated the *Gaia* positions backward to the *GALEX* epoch for every candidate match. A *Gaia*-*GALEX* pair was considered a true match if the propagated *Gaia* position lay within 3" of the *GALEX* coordinates.

Because *GALEX* has a significantly coarser spatial resolution (4.3-6.0" in *FUV* and 5.68.0" in *NUV*) compared to *Gaia* (0.4-0.5"), some *GALEX* detections corresponded to multiple *Gaia* sources. These cases likely reflect blended *GALEX* sources, so we retained all of them. Conversely, some *Gaia* sources matched multiple *GALEX* detections, all of which corresponded to repeated *GALEX* observations of the same object. Our final cross-matched catalogue contains 80.694 million *Gaia*-*GALEX* associations. Now that we have a reliable catalogue of *Gaia*-*GALEX* crossmatches, we used this to create a sample of UV excess objects

In order to constrain this sample to both quality data and limit biases, we applied a number of criteria that each system had to meet. These are;

- (1) $\varpi > 0$,
- (2) $\varpi/\varpi_{\text{e}} > 10$,
- (3) $\text{NUV}_{\text{e}} \leq 0.1$,
- (4) G , G_{BP} and G_{RP} all have data,

(5) $G_{\text{BP}} - G_{\text{RP}} > \text{MIST ZAMS} - 0.5$ (see line in Figure 4.1).

(6) $d \leq 350 \text{ pc}$,

where ϖ is the parallax in mas, and the distance d is calculated by $1000/\varpi$. Criteria (1) and (2) ensure that we are working with systems where we have a robust parallax measurement, which is important for knowing the distance to the system and thus our ability to constrain its absolute magnitudes. Criterion (3) was applied so that we are only working with the systems with high precision *NUV* data. 0.1 mag should ensure such precision, without being too conservative. We do not apply a similar cut in the *FUV*, as there are not as many systems with *FUV* data owing to the *FUV* instrument on *GALEX* becoming inoperative. As a result of this instrumental failure, some of our systems lack *FUV* data.

Criterion (4) was necessary for implementing criterion (5), which removed any obvious single *WDs* along with most *WD* + *dM* systems, which should lie bluer of this line as most *WDs* contribute significantly at optical wavelengths compared to a *dM* companion, and which are not what we are primarily looking for (for how to find such systems and their uses, see Rebassa-Mansergas et al. 2021). A *WD* will contribute negligible flux in optical wavelengths next to FGK stars, with a particularly hot *WD* ($\gtrsim 40 \text{ kK}$) next to a relatively cool K star being required to contribute 10 per cent of the G_{BP} flux.

Criterion (6) allows us to detect a $\log(g) = 8$ *CO* core *WD* with an apparent *NUV* magnitude of 21 with a minimum temperature of $\sim 10,000 \text{ K}$ at our distance limit, which would be too faint beyond our distance, whilst still including a significant number of giant stars, which are lost with smaller distance cuts. We also removed sources where there were 5 or more *GALEX* sources to one *Gaia* source, as such fields are likely too crowded to get a clear idea as to where the *UV* excess may be coming from.

We proceeded to account for reddening using the extinction coefficient from *Gaia* to de-redden our observed magnitudes, and applied the corrections of Wall et al. (2019) to

systems with an apparent magnitude brighter than 15.95 mag in the *FUV*, and brighter than 16.95 in the *NUV*. We used the Andrae et al. (2023) *Gaia* extinctions in order to remain self-consistent, and given that we expect the optically luminous companion to dominate at these wavelengths, these extinction estimates should be not be significantly affected by any contributions from the WD, except for particularly hot WDs in excess of ~ 40 kK next to a particularly cool K star. We applied a further cut in order to remove the bulk of the binary track (this area will contain many active stars in binaries, a potential source of contamination). To make this cut, we removed systems that were redder than 0.5 mag of the MS track, as defined by equation (6) of Kiman et al. (2024), bound by $4 \leq M_G \leq 6.5$ as to not remove evolved stars, and to keep in all K-type stars, as their fit to the MS does not perfectly fit our distribution dimmer than ~ 6.5 mag. This cut, along with the cut of criterion (5) can be see in in Figure 4.1. The colour of these points are explained later in Sections 4.3 and 4.5.2.

Finally, we apply a couple of constraints to the non-degenerate star; we remove systems where the $\log(g)$ is greater than 4.6 in order to reduce the number of M dwarfs, and we remove systems where the effective temperature (T_{eff}), is greater than 12,000 K in order to reduce the number of more massive stars - both $\log(g)$ and T_{eff} being the photometrically derrived GSPPHOT parameters of Andrae et al. (2023). After all of these cuts, we are left with a sample size of 488,148 systems, 111,292 of which have *FUV* data.

One parameter we notably do not make cuts based around is *RUWE* (Renormalized Unit Weight Error Gaia Collaboration et al. 2023b), which is commonly used as an indicator of unresolved binarity, as it measures how well a given source matches a single star model. A non-optically luminous companion can cause an astrometric ‘wobble’ in the photocentre of the binary, which would increase the measured *RUWE* value, and which would affect parallax measurements (see e.g. El-Badry 2025). We however do not implement a cut on *RUWE*, as doing so would either remove very close systems (which have a low *RUWE*), or very wide systems (which have a high *RUWE*) - which would

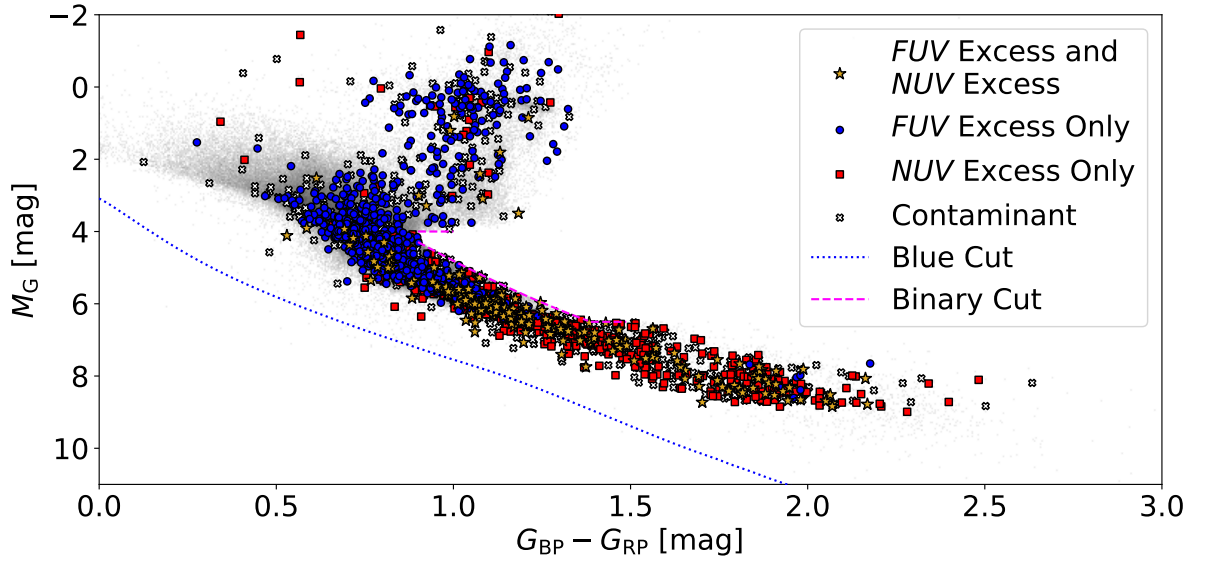


Figure 4.1: *Gaia* optical colour magnitude diagram displaying where our excess systems lie in *Gaia* optical colour space. Our systems with an excess in both UV bands are shown as golden stars, where there was only a FUV excess as blue circles, systems with only an NUV excess as red squares and likely contaminants as a white cross. These ‘Contaminants’ are flagged based on the ‘Contaminants’ column in the supplementary table. The blue dotted line represents to optical blue cut we made to remove lone WDs and most WD + dM binaries from our initial sample (criterion (5)), and the dashed magenta line represents the cuts we made to remove the binary track.

thus reduce the completeness of our sample, as we wish to include both in our sample.

4.3 Method

4.3.1 Defining the Excess Sample

In order to identify objects with UV excesses, we matched each of our systems with MIST models for *Gaia* and *GALEX* wavelengths using tracks matched using *Gaia*'s parameters for $\log(g)$, metallicity (likewise Andrae et al. 2023) and T_{eff} of the non-degenerate component, along with their respective errors, in order to approximate the magnitudes of the star without any contributions from the WD. For simplicity, ‘Observed’ will be used hereafter to refer to the observed and de-reddened absolute magnitude, and ‘Model’ will refer to the MIST isochrone value corresponding to the *Gaia* parameters of the source.

A clear offset can be seen between the predicted UV magnitudes from the MIST models and the observed *GALEX* UV magnitudes, as can be seen in the top-left panel in both Figure 4.2 and in Figure A.2, which we suspect is owing to the MIST models not accounting for chromospheric activity, which can be particularly strong at UV wavelengths (Smith & Redenbaugh, 2010). To correct for this, we fit a number of 2D polynomials to the distribution (top right panel) for both *FUV* and *NUV* bands assuming that the vast majority of the sample do not have a UV excess, but are representative of the typical UV fluxes of normal, isolated stars. These polynomials were fit in 5 different regions to best match the distribution, these regions being split by the following lines;

- (a) $T_{\text{eff}} = 1250 \log(g)$,
- (b) $T_{\text{eff}} = (1000 \log(g)) / 3 + 4466$,
- (c) $T_{\text{eff}} = 3500$ when $\log(g) \geq 2.8$,
- (d) $\log(g) = 2.5$ when $3125 < T_{\text{eff}} \leq 5300$,

These zones thus correspond to;

- (i) right of both lines (a) and (c),
- (ii) right of line (a) but left of line (c),
- (iii) left of line (a), right of line (b) and above of line (d),
- (iv) left of line (a), right of line (b) and below line (d),
- (v) left of line (b).

The resultant polynomial corrections to the *MIST* models, given in the form

$$A + B \log(g) + C T_{\text{eff}} + D \log(g)^2 + E \log(g) T_{\text{eff}} + F T_{\text{eff}}^2 \quad (4.1)$$

for each zone, with the coefficients $A - F$ given in Table 4.1.

Table 4.1: The polynomial coefficients subtracted from the **MIST** models across the different zones in order to correct the model offsets. The polynomials take the form of $A + B \log(g) + C T_{\text{eff}} + D \log(g)^2 + E \log(g) T_{\text{eff}} + F T_{\text{eff}}^2$

Zone	<i>NUV</i> Polynomial Coefficients						<i>FUV</i> Polynomial Coefficients					
	<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>	<i>E</i>	<i>F</i>	<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>	<i>E</i>	<i>F</i>
(i)	1665	-248	6.68 10 ⁻¹	6.26 10 ⁻¹	7.19 10 ⁻²	5.42 10 ⁻⁵	467	-352	1.47 10 ⁻¹	7.27	8.24 10 ⁻²	-7.06 10 ⁻⁵
(ii)	-12.5	-28.5	2.74 10 ⁻²	2.42	1.91 10 ⁻³	-3.48 10 ⁻⁶	-324	97.9	3.38 10 ⁻²	-12.4	2.54 10 ⁻³	-3.81 10 ⁻⁶
(iii)	43.4	18.4	-2.75 10 ⁻²	5.81 10 ⁻¹	-4.44 10 ⁻³	4.03 10 ⁻⁶	-12.5	12.4	-1.11 10 ⁻²	5.23 10 ⁻¹	3.39 10 ⁻³	2.64 10 ⁻⁶
(iv)	-4.13	4.02	-8.93 10 ⁻⁴	1.47 10 ⁻¹	-9.52 10 ⁻⁴	4.15 10 ⁻⁷	-126	-6.02	4.56 10 ⁻²	-1.63	3.16 10 ⁻³	4.77 10 ⁻⁶
(v)	11.3	-3.79	-4.17 10 ⁻⁴	4.57 10 ⁻¹	-6.85 10 ⁻⁵	4.22 10 ⁻⁸	8.28	5.03	-4.65 10 ⁻³	-1.18	6.76 10 ⁻⁴	1.08 10 ⁻⁷

When combined, these produce the residuals shown in the bottom-left panel of Figure 4.2 in the *FUV*. The *NUV* (Figure A.2) looks similar, and in both cases no clear structure is seen in these residuals. We also investigated the effects of metallicity, though found no systematic trends and thus we did not need to apply any corrections based on this factor. Finally, any systems that had an excess (Observed - Model - Polynomial) greater than a set value, ΔM_{Limit} were flagged as being an excess in that band. ΔM_{Limit} was found by comparing each point to its 250 nearest neighbours within $\log(g) / T_{\text{eff}}$ space, with a maximum normalised radius of 0.2 (i.e. 20 per cent of parameter space), against each other, taking 3 standard deviations of this value for *FUV* or 5 standard deviations in *NUV*. We used the stricter 5σ criterion for the *NUV* band because some MS stars (especially F and early G) can contribute significantly in the *NUV*, so a stricter cut-off was necessary to account for this. We find that 8 of the 9 of the previously known WD + FGK systems from Holberg et al. (2013) that were in our sample after all the cuts and quality checks were flagged as an *FUV* excess system, whilst of the 10 that were in the *NUV* sample (as one did not have *FUV* data), only 3 were flagged as having an *NUV* excess. HD 13611 was not flagged in either band - though this is a relatively cool WD at $T_{\text{WD}} \approx 13 \text{ kK}$ (Holberg et al., 2013), which would make it difficult to detect (see Section 4.5.1).

We found a total of 1744 systems being flagged as having an *FUV* excess, and 1257 having an *NUV* excess, with 404 being common between the two as can be seen in Figure 4.3, for a total excess sample size of 2597. Their locations in both *Gaia* and UV Colour Magnitude Diagrams (CMDs) can be seen in Figures 4.1 and A.1.

4.3.2 Acquiring WD Parameters

With our sample of excess systems collated, we must now evaluate the parameters of our candidate WD - as it is possible that this UV excess may be from another source.

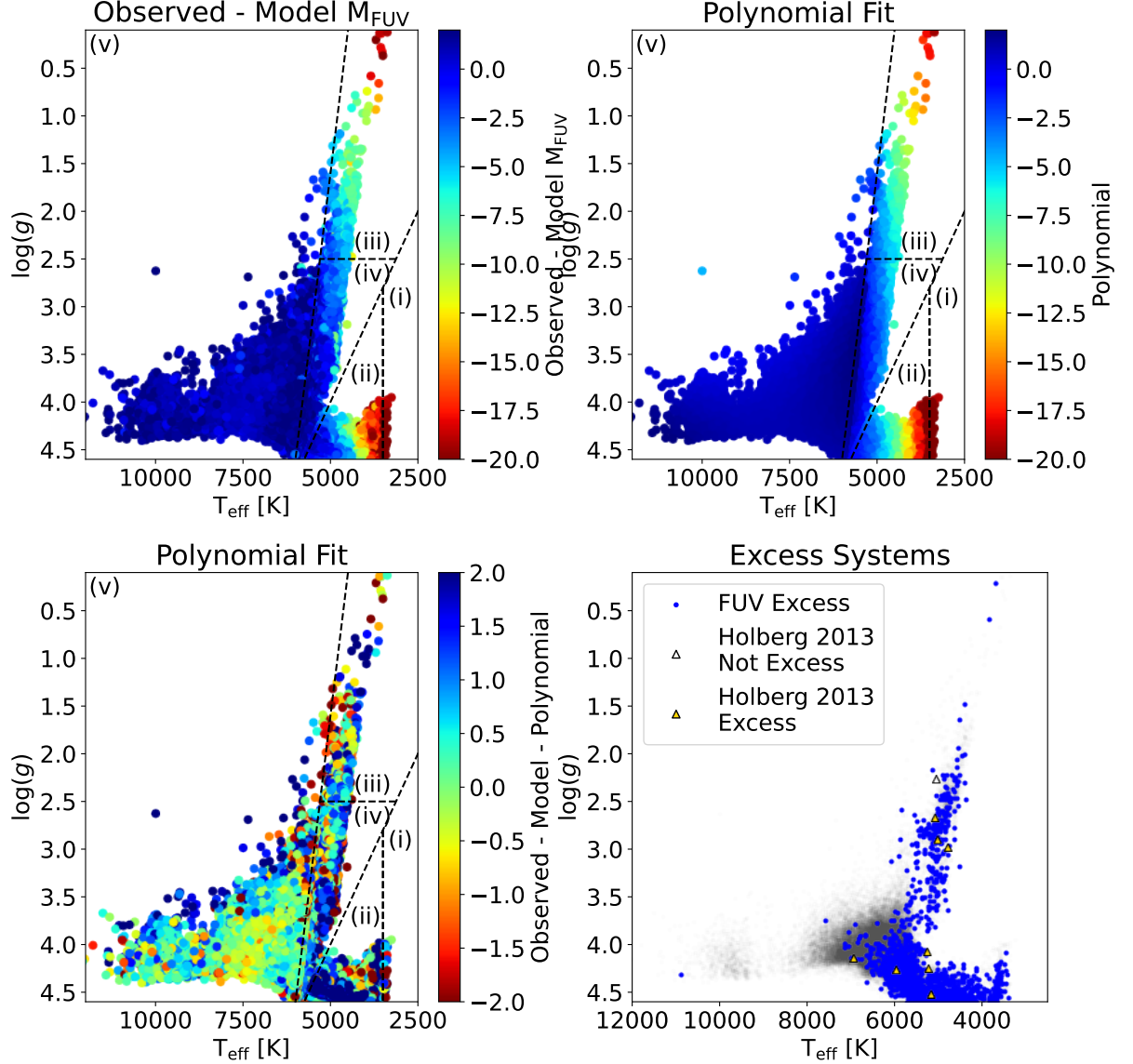


Figure 4.2: Kiel diagrams of the 111,292 objects in *Gaia* DR3 with measured parameters, within 350 pc and with a *FUV* detection in *GALEX*. The top left panel is colour-coded by the observed, absolute de-reddened *FUV* magnitude minus the *MIST* model magnitude of the system as found by fitting the T_{eff} , $\log(g)$ and Fe/H of the system. The top right panel is colour-coded to show the polynomial fit to the distribution, and the bottom left shows the residuals after the polynomial corrections are subtracted. The dashed lines indicate the boundaries of the different regions where different polynomials were fit. The bottom right panel shows our systems that were flagged as an excess, with the known WD + FGK systems from Holberg et al. (2013) shown as triangles.

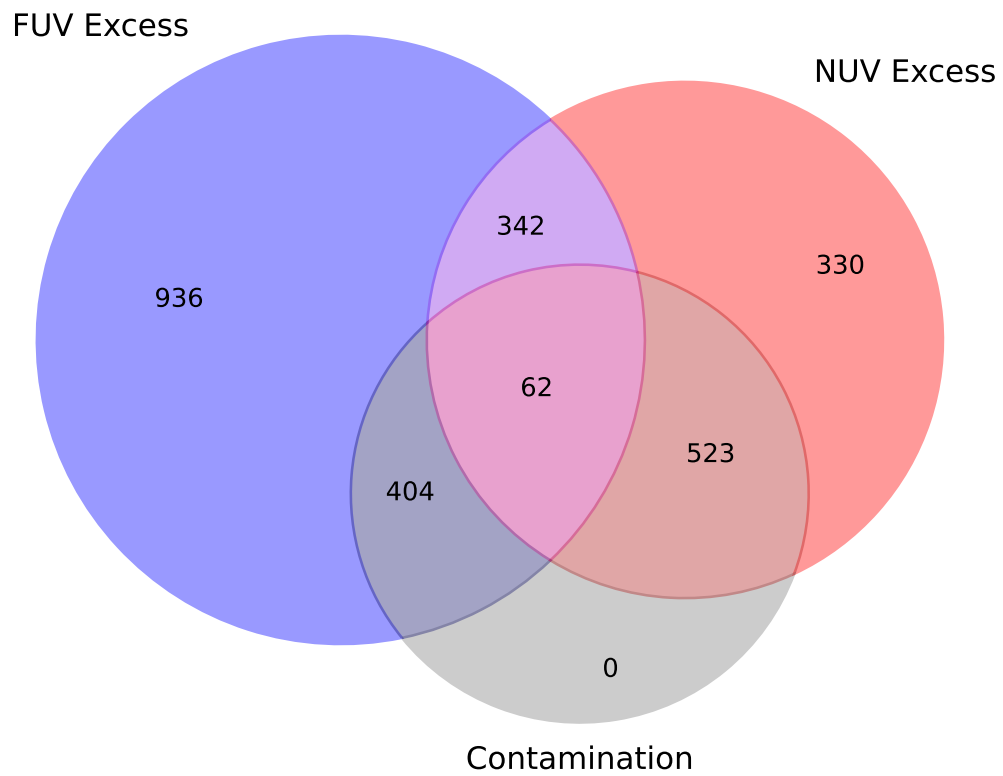


Figure 4.3: A set diagram showing the breakdown of which systems are flagged as having a *FUV* and/or *NUV* excess, along with the numbers of each which are flagged as contaminants (see Section 4.5.2).

Working under the initial assumption that the UV excess is caused by a WD, we subtract the corrected UV flux of the non-degenerate companion from the observed UV fluxes to obtain the UV flux attributed to the excess. This did not always result in there being a flux in both bands for the WD; not all of our systems have FUV data, and in many cases there was an excess in one band but not the other. Overall, we have five scenarios;

- (i) There is both an FUV and NUV excess in the system,
- (ii) There is a clear FUV excess but only a marginal excess in the NUV,
- (iii) As above, but with the bands reversed,
- (iv) There is a clear FUV excess, but no NUV excess,
- (v) There is a clear NUV excess, but no FUV excess, either because there is no FUV data, or because there was no excess in the FUV.

Here, ‘marginal’ meaning that, while there is an excess in the band, it is too small to be attributed to a WD given the excess in the other band. In case (i), we perform a fit to the UV excess, using the DA CO core models of Bédard et al. (2020) using a least squares χ^2 minimization, with an initial parameter guess of $\log(g) = 8$ and $T_{\text{eff}} = 10,000$ K, and repeat increasing our T_{eff} initial guess by steps 1000 K up to 90,000 K in order to avoid falling into local minima. We fit here using $\log(g)$ as a proxy for R using the well tested mass-radius relationships of WDs (see e.g. Holberg et al. 2012; Tremblay et al. 2017; Parsons et al. 2017; Bédard et al. 2017).

In cases (ii) and (iii), we have fewer input parameters to work with. We vary the $\log(g)$ input from 7 to 9 in steps of 0.1, and calculate the WD T_{eff} and M_{WD} based on this $\log(g)$ and the WD flux in the excess band. We also extract the absolute magnitude of the non-excess band, and reject the results if this UV magnitude would have been flagged as an excess in this other band. We take our final result as the values associated with the median $\log(g)$ of the non-rejected results.

Table 4.2: The number of systems fitted with each of our different fitting methods to determine the WD parameters.

Fitting Method	Number
(i) Both Fit	404
(ii) Both Data, <i>FUV</i> Excess Only	729
(iii) Both Data, <i>NUV</i> Excess Only	44
(iv) <i>FUV</i> Data Only	320
(v) <i>NUV</i> Data Only	730

In cases (iv) and (v), we cannot do a proper fit. Instead, we interpolate using the band which has data and assuming a fixed $\log(g) = 8$ to find the T_{eff} and M_{WD} .

The breakdown of each case can be observed in Table 4.2. Not shown in the table are cases where the fitting methods failed. We find that 180 systems fail from case (ii), 56 fail in case (iii), 111 fail in case (iv), and 23 fail in case (v). There are no failed systems in cases (i). These ‘failed’ systems are owing to the parameters input in each case being unable to find a T_{eff} within the grid, and are flagged with flag ‘1’ in the ‘Contamination’ column of the supplementary table. These systems likely represent contaminants from active stars where the shape and strength of the UV excess is incompatible with a WD. However, this does not guarantee that all the rest of our sample is free from contamination as it is possible for activity to strongly mimic the SED of a WD at UV wavelengths (e.g. Garbutt et al. 2024).

As can be seen in Figure 4.4, when we consider our case (i) systems, we are most sensitive to lower mass WDs, which is unsurprising given that such WDs will be larger and more luminous, and thus more likely to have a UV excess. We compare our case (i) parameters against those from the astrometric sample of Garbutt et al. (2024), the WD + dM sample of Rebassa-Mansergas et al. (2021) and the 40 pc single WD sample of O’Brien et al. (2024). We can see that, much like Garbutt et al. (2024) and Rebassa-Mansergas et al. (2021), we are sensitive to lower mass WDs, even more so than these samples. This result is expected in our sample, as we expect to find post-SMT binaries, which should have lower mass WDs - this is not the case in Rebassa-Mansergas et al.

(2021), where their excess of very low mass systems is a result of their fitting method. This is in contrast to the 40 pc single WD sample of O'Brien et al. (2024), which lacks the selection effects of the other samples in the comparison, which rely on more luminous WDs. However, there may still be a genuine difference in the mass distribution of binary vs single WDs, as binary interactions may result in mass loss.

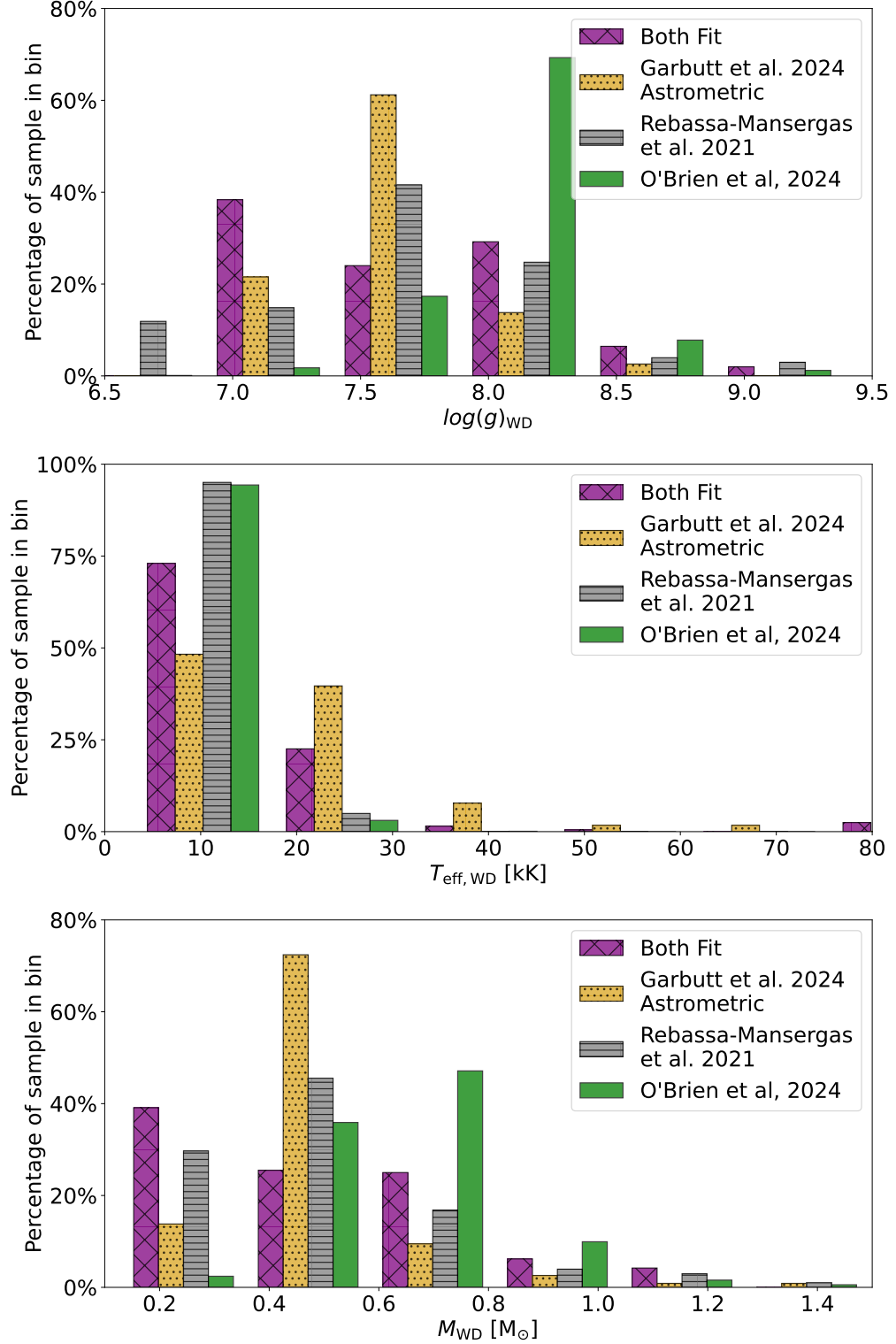


Figure 4.4: Histograms displaying the case (i) WD parameters found from our fitting, shown in purple with crossed hatching, along with the same properties from the Astrometric sample of Garbutt et al. (2024) (as this sub-sample is more robust than the Spectroscopic sample of the same paper) shown in a yellow bar with a dotted hatch, the WD + dM sample of Rebassa-Mansergas et al. (2021) shown as a grey bar with a horizontal hatch, and the 40 pc sample of single WDs from O'Brien et al. (2024), shown as a solid green bar.

4.4 Crossmatching

With our excess samples acquired, we crossmatched with various external catalogues. The purposes of each crossmatch varied depending on the catalogue - from constraining the WD parameters better to identifying possible sources of contamination. A breakdown of the number of sources present in each crossmatch is given in Table 4.3.

4.4.1 Clusters

It can be hard to constrain the age of WD + MS binaries post mass transfer, as the two components have been affected by binary interactions, potentially erasing or resetting any age indicators. One way to constrain the ages of our systems would be if they belong to any clusters, as the population of the cluster should have the same age. To this end, we matched against the cluster catalogue of Hunt & Reffert (2024), finding that 30 of our systems are flagged as being a member of a cluster. A breakdown of these 13 systems can be seen in Table A.1 in Appendix A.2. Anything younger than 35 Myr is too young to host a WD (Yan et al., 2025) and are flagged as ‘2’ in the ‘Contamination’ column in the supplementary table. For those clusters of around $\lesssim 10$ Myr, these could potentially be young stellar objects (Grankin, 2016).

4.4.2 Spatially Resolved Binaries

An alternate way of determining the age of the system is if there is a wide WD companion to the inner binary, i.e. a triple - as these stars would have all formed simultaneously, and finding the age of the distant WD that has not undergone binary interactions is fairly simple - simply adding the lifespan of the progenitor (based on the IMF relationship) and the WD cooling age (see for example Rebassa-Mansergas et al. 2021). We crossmatched with the catalogue of spatially resolved binaries of El-Badry et al. (2021), finding 741 matches. Not all of these are WD + MS binaries however - most are flagged

Table 4.3: A breakdown of the number of systems in each crossmatch. The radii given in the brackets next to SIMBAD, ROSAT and eROSITA are the sky-search radii used in crossmatching.

Catalogue	Sample (2597)
Cluster Member	13 (1%)
Spatially Resolved Binaries	741 (29%)
SIMBAD (2")	1618 (62%)
<i>Gaia</i> nss_acceleration_astro	161 (6%)
<i>Gaia</i> nss_non_linear_spectro	19 (1%)
<i>Gaia</i> nss_two_body_orbit	155 (6%)
<i>of which are astrometric</i>	86 (3%)
<i>of which are single-lined spectra</i>	62 (2%)
ROSAT (10")	126 (5%)
eROSITA (2")	66 (3%)

as **MS** + **MS** binaries, meaning the wide companion to our inner binary is a **MS** star - for which it is harder to determine the age. 65 of these matches are flagged as **WD** + **MS** binaries.

It is possible that, of these 65, the **UV** flux that we have attributed to our inner binary has actually come from this wider **WD**. To check this, we matched the *Gaia* source id of the wide companion back with our original *Gaia*-*GALEX* crossmatch table, and find 60 matches. All of the binaries with a angular separation, ϕ , of $<\sim 5''$ have the same **UV** readings for both the inner object and the wide **WD** companion, suggesting that in these systems the entirety of the **UV** flux could come from this companion, and the inner object may indeed be a lone **MS** star. Of our whole excess sample, 652 of the 2597 (25 per cent) have another **UV** source within $5''$, with 631 of these having the same *GALEX* object ID, though none of our excess objects are within $5''$ of one another. See Section 4.5.2 for a discussion of this potential contamination within our sample.

We have 7 systems with a **WD** common proper motion companion and ϕ greater than $5''$, though 3 of these lacked *GALEX* data attributed to the wide companion's *Gaia* source ID. Of the remaining 4 (WDJ082950.68+311257.30, WDJ083345.82+431745.64, WDJ085618.03+003758.87 and WDJ141407.54+831624.61), the difference between the

Table 4.4: The 4 wide systems in our crossmatch with El-Badry et al. (2021) with a distant WD companion to the UV excess object - too far away to be responsible for the UV excess, detailing their angular separation, the differences in the UV magnitudes between the wide companion and the inner binary, and the predicted age of the system.

WD	ϕ ["]	ΔM_{FUV}	ΔM_{NUV}	Age [Gyr]
WDJ082950.68+311257.30	25.7	0.28	0.03	-
WDJ083345.82+431745.64	11.9	-	1.66	3.37
WDJ085618.03+003758.87	5.3	0.47	-	4.17
WDJ141407.54+831624.61	37.7	3.38	1.08	-

UV magnitudes detected is promising that there is indeed an inner WD + MS binary in 2 of these systems, detailed in Table 4.4.

We attempted to calculate the ages of these 4 systems using the `WDWARFDATE` python package (Kiman et al., 2022; Cummings et al., 2018; Bédard et al., 2020; Dotter, 2016; Choi et al., 2016), assuming a DA WD and using the DA WD properties of Gentile Fusillo et al. (2021). We find a cooling age of 3.73 Gyr for WDJ083345.82+431745.64 and 4.17 Gyr for WDJ085618.03+003758.87, though the package was unable to calculate an age for WDJ082950.68+311257.30 or WDJ141407.54+831624.61 due to the estimated very low masses of the WDs (each around $0.4 M_{\odot}$), outside the initial-final mass relation (IFMR) used by the model and thus it was unable to calculate the MS age for either system.

4.4.3 *Gaia* Non-Single Stars

Given we are looking for what is optically a single source, but with a secondary hidden component, the *Gaia* catalogues of such systems should provide us with a good match to what we are looking for, along with letting us see if we are looking at genuine close binaries opposed to chance alignments. To this end, we crossmatched our results with the *Gaia* non-single stars catalogues (`nss_acceleration_astro`, `nss_non_linear_spectro`, `nss_two_body_orbit` and `nss_vim_fl`) to look for confirmed binaries. `nss_acceleration_astro` is a catalogue where the optical source shows signs of astrometric acceleration that is best de-

scribed by a quadratic or cubic fit, `nss_non_linear_spectro` is similar, except for spectroscopic binaries opposed to astrometric binaries. `nss_two_body_orbit` is the simplest, containing the linear fits of the binaries and `nss_vim_fl` are systems where one of the binary components is a variable star, causing a shift in the photocentre of the system what required corrections to the astrometric parameters used in fitting the system (Gaia Collaboration et al., 2023c).

We find 161 matches with `nss_acceleration_astro`, 19 in `nss_non_linear_spectro`, 155 in `nss_two_body_orbit`, and none in `nss_vim_fl`. Of particular interest to us are the `nss_two_body_orbit` results, as we can get a WD mass from these results as in Garbutt et al. (2024). We find that of the 155 crossmatch results, 86 are astrometric systems and 62 are single-lined spectra, with the remaining 7 consisting of 6 double-lined spectroscopic binaries and one eclipsing binary, which are unlikely to be WD + FGK binaries, as a WD should contribute a negligible amount of optical flux compared to an F, G or K stellar type companion. A WD may contribute optically in a WD + dM binary, so in theory these 7 systems could have been a WD + dM, however inspecting the *Gaia* colour magnitude diagram reveals that the eclipsing binary and 5 of the double lined spectroscopic binaries are F/G type MS stars, and the final double-lined spectroscopic system is an evolved star sitting above the horizontal branch - ruling out these systems being WD + dM systems.

4.4.4 Simbad

The biggest repository for us to check for contamination against would be SIMBAD (Wenger et al., 2000). We crossmatched with SIMBAD using a 2" sky search, converting our RA and dec to J2000 to do so. In particular, we were hoping SIMBAD would help us catch binary systems with an active star but no WD, pre-MS stars and poorly matched sources. In total, 1618 of our 2597 systems were successfully matched to a SIMBAD

Table 4.5: A breakdown of the broad categorizations of SIMBAD flags of interest. It should be noted that these categories can overlap, with systems being flagged as both ‘Binary’ and as ‘Eclipsing Binary’ separately. We have also not included in these numbers ‘candidate’ systems, as these may not be contaminants.

Flag	Sample (1618)
Binary Star	173 (11%)
Cataclysmic Variable	1 (0%)
Eclipsing Binary	43 (3%)
Erupting Variable	9 (1%)
Galaxies	10 (1%)
Planetary Nebulae	2 (0%)
Planet Candidate	3 (0%)
White Dwarfs	16 (1%)
Young Stellar Objects	20 (4%)

source.

To identify sources of contamination, we checked both the main type flagged by each object by SIMBAD, and the list of other types flagged. Broadly, we can split our types of interest into the following categories; Binary Stars, Erupting Variables, Galaxies, Planetary Nebulae, Planet Candidates, White Dwarfs and Young Stellar Objects. A summary of the breakdown of how many of each were flagged can be seen in Table 4.5.

Binary Stars

Given we are searching for WD + FGK binaries, one might think that things being flagged as a binary is a promising sign - however, it is not so simple, as we suspect that binary systems containing an active star may be a source of contamination, as chromospheric activity can cause an excess of UV flux (Smith & Redenbaugh, 2010; Shkolnik et al., 2014; Smith, 2018). We made attempts to reduce the number of active MS + MS binaries by removing the binary track (see Section 4.2), though it is likely that this remains a source of contamination within our final sample. We find that our flagged binaries cover the full range of the optical colour-magnitude diagram, from evolved stars to M dwarfs, as can be seen in Figure 4.5.

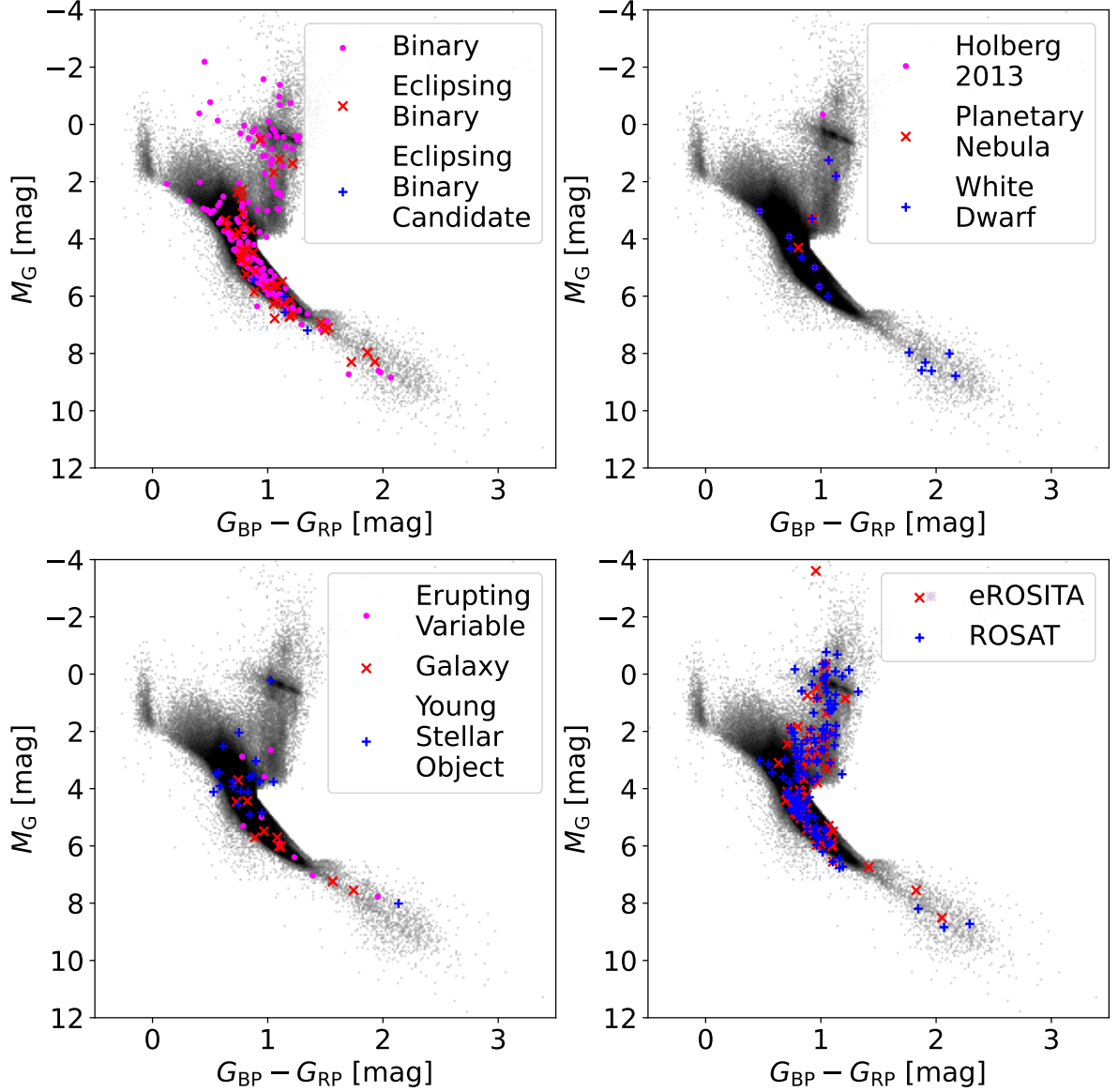


Figure 4.5: *Gaia* optical colour-magnitude diagrams of our various crossmatches. The top left panel shows binaries (pink points), eclipsing binaries (red crosses) and eclipsing binary candidates (blue pluses) from our SIMBAD crossmatches, the top right panel shows the [Holberg et al. \(2013\)](#) systems within our sample (pink points), along with the planetary nebulae (red crosses) and WDs found from our SIMBAD crossmatch. The bottom left panel shows the erupting variables (pink points), alleged galaxies (red crosses) and young stellar objects (blue pluses) from our SIMBAD crossmatch, and the bottom right shows the systems from our eROSITA crossmatch (red crosses) and ROSAT crossmatch (blue pluses).

Eclipsing Binaries

Eclipsing binaries provide an indication that a system is unlikely to be a true WD + FGK candidate, as a WD does not contribute enough optical flux to undergo an obvious or deep eclipse, with the rare exception of an extremely hot WD next to a very late-type K dwarf, such as V* V471 Tau, a known WD + K binary which is found within our sample.

Indeed, we find 2 known WD binary candidates in our eclipsing sample that are not flagged as containing a WD by SIMBAD; CRTS J152748.4+353657 and V* V648 Aur. Eclipsing binaries (sans these 2 exceptions) are flagged as ‘3’ in the ‘Contamination’ column of the supplementary table.

CRTS J152748.4+353657 is disputed as being either a WD + dM system or being a neutron star (NS) + K system. This latter proposal is explored by Lin et al. (2023), whilst the former by Zhang et al. (2024); Zhao et al. (2024). Zhang et al. (2024) explains that this arises from Lin et al. (2023) finding an inclination of ~ 45.2 deg, whilst Zhang et al. (2024) find an inclination of ~ 63 deg, which led to the former getting a mass of $0.98 M_{\odot}$, and the latter $0.69 M_{\odot}$. Zhao et al. (2024) independently found a mass of $0.67 M_{\odot}$, in good agreement with Zhang et al. (2024). We fitted this system with *NUV* data and found a M_{WD} of $0.62^{+0.58}_{-0.38} M_{\odot}$. This mass combined with the UV excess leads us to conclude that the companion is most likely a WD.

V* V648 Aur is a RS Canum Venaticorum variable (RS CVn), a type of variable system defined by chromospheric activity within a close binary, with Lloyd et al. (2007) identifying this system as being a short period (~ 0.47 d) RS CVn with a K type star. It appeared as a candidate WD + FGK system in Ren et al. (2020), however we cannot conclusively say whether this system contains a WD; only that it has been flagged as a candidate, since this type of active binary can be with or without a WD component. We find a M_{WD} of $0.63^{+0.58}_{-0.37} M_{\odot}$.

Galaxies

We look here to figure out why we have seemingly flagged 10 galaxies - these could be genuine background galaxies, leading to UV contamination - or if the ‘Galaxy’ classification is simply a miscategorisation. We flag these galaxies with a ‘4’ in the ‘Contamination’ column of the supplementary table. Images of these four galaxies can be seen in Figure A.3.

2MASX J10500333+1538485 was matched with *Gaia* DR3 3981520724472295168, which does not have its own entry within SIMBAD (2MASX J10500333+1538485 has its own DR3 identifier; *Gaia* DR3 3981520720177408384). 2MASX J10500333+1538485 is flagged as a Seyfert 1 galaxy and as quasar (Véron-Cetty & Véron, 2010). It is likely, given the differing DR3 identifiers and previous studies, that this is a background galaxy with *Gaia* DR3 3981520724472295168 in the field.

2dFGRS TGS154Z168 was matched to *Gaia* DR3 5120883704520804736, which itself does not have its own entry within SIMBAD. This was proposed in the 2dF Galaxy Redshift survey of Colless et al. (2001). Given that this survey was taken pre-*Gaia*, and our reasonably robust parallax requirements, it is likely that this is a miscategorisation.

2dFGRS TGS392Z063 has a similar story to that of 2dFGRS TGS154Z168 - it was matched to *Gaia* DR3 5067287254311288064, which again does not have its own SIMBAD entry. Likewise a product of Colless et al. (2001), it is likely a miscategorisation.

ATO J214.6107+00.2412 was flagged as a galaxy by the Millennium Galaxy Catalogue (Liske et al., 2003), however it is primarily flagged as a variable star, and is confirmed as a star by *Gaia*. It is therefore another example of a previous miscategorisation.

LEDA 2094596 was matched with *Gaia* DR3 760733820172658560 - which does not have its own entry in SIMBAD. LEDA 2094596 was initially flagged as a galaxy by Paturel et al. (2003), and later by Moustakas et al. (2023). Given the recency of this

latter study, we conclude that this is likely a background galaxy.

MCG-06-04-041 is a very obvious galaxy, as can be observed in panel 6 of Figure A.3 in Appendix A.3. This system has the correct *Gaia* DR3 source ID - making it's inclusion interesting as a well studied galaxy (see e.g. Corwin et al. 1985; Moustakas et al. 2023) with a robust *Gaia* parallax placing it within 350 pc. It is likely then that this is a background galaxy, where the star detected by *Gaia* is positioned incredibly close to the galactic nuclei along *Gaia*'s line of sight.

SDSS J093815.73+663622.8 appears in Toba et al. (2014), which flags it as a galaxy - however it is confirmed by *Gaia* as being a star. We conclude then that this is yet another system previously miscategorised as a galaxy, given the robust parallax measurements of *Gaia*.

TYC 4986-553-1 is primarily flagged as a star in SIMBAD. It appears in Liske et al. (2003) and no other sources. As with our prior examples, we have a robust parallax for this system, so it is likely a miscategorisation.

UCAC4 234-000552 was investigated by the European Large Area ISO Survey (Lari et al., 2001; Rowan-Robinson et al., 2004), which is known to have both stellar and extragalactic sources. It has also been the target of the RAdial Velocity Experiment (RAVE) surveys (Kordopatis et al., 2013; Kunder et al., 2017; Steinmetz et al., 2020), suggesting that this system is a star, and that the galaxy flag is a result of a miscategorisation.

Finally, [HM2015b] 96 1 was matched to *Gaia* DR3 3981915444851588992, which does not have its own SIMBAD entry. [HM2015b] 96 1 is allegedly a UV source galaxy which is part of a star-forming compact group of galaxies (Hernández-Fernández & Mendes de Oliveira, 2015), though the parallax of this systems is robust, and appears in the *Gaia* `nss_acceleration_astro` catalogue. It being flagged as a galaxy is thus a miscategorisation of a star from an earlier misunderstanding of what the system was.

White Dwarfs

We find 16 WDs in our SIMBAD crossmatch. Most (10) of these are known WD binaries, or established WD binary candidates, detailed in Table A.2. 6 systems however are currently flagged as lone WDs in SIMBAD - however these lie on the MS track in the *Gaia* CMD (see the top-right panel of Figure 4.5). These are cases where SIMBAD has matched with a nearby resolved WD, which can be found in Gentile Fusillo et al. (2019). Five of these systems show up within our 5" search for nearby objects (see Section 4.5.2, with the sixth being a proper common motion WD + MS binary, where the WD is around 6" away from the MS target). Two of our flagged WDs, BD+08 102 and PN A66 35, are discussed in more detail in the ‘Systems of Interest’ section.

Young Stellar Objects

T Tauri variables produce a UV excess compared to MS stars (Joy, 1945, 1954; Herbig, 1962, 1970; Sullivan & Kraus, 2022) as disc material accretes onto young star, and thus could be considered a potential source of contamination. However, these usually lie to the red of the MS track on the optical CMD, whilst those flagged in our sample are found spread over the full range of the optical CMD, as can be observed in Figure 4.5, with a slight over density sitting just below the MS, which we would not expect. We flag young stellar objects with the number ‘5’ in the ‘Contamination’ column of the supplementary table.

Systems of Interest

One of our systems, BD+08 102, is flagged as cataclysmic variable. However, BD+08 102 is unlikely to be a cataclysmic variable; it was first identified as a candidate WD + K binary by Kellett et al. (1995), and subsequent papers (such as Leiner et al. 2018; Sun et al. 2024), along with its appearance in *Gaia*’s `nss_acceleration_astro` catalogue

suggest that it is a relatively wide binary. It is likely that this source was miscategorised as a cataclysmic variable owing to the presence of X-ray sources, which we instead believe to be coming from the rapidly rotating star, which is likely active.

We also found two apparent planetary nebulae - PN A66 35 and PN K 1-6. Such systems will have a UV excess caused by the now exposed core of the progenitor star of the nebulae, with the heated ejected material still providing more optical light than a lone WD.

However, it is likely that PN A66 35 has been miscategorized and is not actually a planetary nebula, but rather an unrelated hot HII region ionized by a hot pre-WD (Frew 2008; Tyndall et al. 2013; Jacoby et al. 2021, under the name Abell 35 or A35), and can be seen in Figure A.4. This pre-WD has only recently formed, and it is likely that the two progenitor stars had similar initial masses, given the companion star seems to be a G8 giant or subgiant nearing the end of its life, implying similar age (Ziegler et al., 2012). Given the relatively long orbital period of ~ 790 d and their similar initial masses, this is a promising post-SMT candidate, as such systems are expected to form when the initial mass ratio is near 1, and are expected to emerge from the period of mass transfer with a relatively long orbital period. PN K 1-6 is itself a candidate for being a WD + G/K binary, though this is not the only proposed classification for this system - with it being a hot subdwarf binary also being likely (Frew et al., 2011).

3 of our systems are flagged as potentially hosting exoplanets - HD 102888c, TOI-1893.01 and TOI-659.01, with these latter two being detected by their transits. We care about this as a WD transit and an exoplanet transit can mimic one another, making this a method for discovering WD binary candidates. In the case of TOI-659.01, the fit to the transit implies an object of $\sim 1 R_{\text{Jup}}$ - far too large to be a WD. TOI-1893.01 has a radius of $\sim 4 R_{\oplus}$, which could be consistent with a hot low mass WD - though more observations would be required to confirm the presence of a WD.

4.4.5 ROSAT and eROSITA

X-rays can be an indication for the presence of a WD in an interacting binary - as X-rays are produced during both accretion from Roche-lobe overflow, and also by wind accretion (Kuijpers & Pringle, 1982; Patterson & Raymond, 1985; Mukai, 2017). However, they can also be produced by active stars - so the presence of X-rays is not confirmation that the system contains a WD, but is rather a flag for potential further follow up.

We matched with the second ROSAT all-sky survey (Boller et al., 2016) and the SRG/eROSITA all-sky survey (Merloni et al., 2024) to see if we have matches with x-ray catalogues. We find 84 matched systems with the ROSAT survey using a 10" search radius, and 55 matches with the eROSITA survey using a 2" search radius. These matches seemingly span the full optical CMD, as seen in the bottom-right panel of Figure 4.5.

We find that our system flagged as a cataclysmic variable in SIMBAD does indeed appear in the ROSAT survey, though it does not appear in the eROSITA survey. We also find that 6 of the WDs flagged by SIMBAD appear in ROSAT (* 29 Dra, BD+08 102, CPD-65 264, HD 18131, HD 90052 and V* V471 Tau), and 2 appear in eROSITA (CPD-65 264 and TYC 110-755-1). Most are short period systems with active stars, so X-rays could originate from either or both components.

4.4.6 Checks for Activity

Another potential source of a UV excess within a system, aside from a hidden WD, is stellar activity. We make two checks for stellar activity. First, we checked against the catalogue of known active FGK stars of Gomes da Silva et al. (2021), though we find only one result - HD 16522. We also check for activity using `activityindex_espcs` (Creevey et al., 2023), a measure of stellar activity determined using Ca II emission. Following the method of Lanzafame et al. (2023), we find 143 of our systems are flagged as having very high activity, 544 as having a high activity, and 408 as being low activity.

The remaining 1502 systems do not have a measurement of `activityindex_espcs`, so we cannot measure activity using this method. We do not however flag the presence of activity within the ‘Contamination’ column of the supplementary table, as the object could be a lone active star or an active star in a binary with a WD, as many active stars exist in binaries (see e.g. [Hernandez et al. 2022b](#)).

4.5 Completeness and Contamination

4.5.1 Completeness

We do not expect that our sample of 2597 systems is complete. We are insensitive to cooler WDs, particularly next to hotter stars. To get an idea of what we are missing within our target range, we determined the maximum $T_{\text{eff,MS}}$ for which a WD of given parameters can be detected, so we know which objects will have eluded our search. We are looking specifically at MS stars here, defined as having `evolstage_flame` (a *Gaia* parameter determining the life cycle phase of a stellar object using BaSTI models (Hidalgo et al., 2018; Creevey et al., 2023)) ≤ 360 , opposed to giants, as MS stars are more predictable than giant stars, and we do not have a statistically significant number of giant stars to compare against.

In order to determine which WDs were detectable next to what MS star, we binned our MS stars that made it past our initial cuts in Section 4.2 prior to our UV excess selection by their T_{eff} in steps of 100 K, but widening the bins in steps of 100 K until there was at least 1000 systems in each bin. We averaged the T_{eff} , $\log(g)$, $M_{\text{NUV,Obs}}$, $M_{\text{FUV,Obs}}$, $M_{\text{NUV,MIST}}$ and $M_{\text{FUV,MIST}}$ in each bin, and used these to create a polynomial fit to the UV magnitudes.

We compared a grid of CO core WD models of Bédard et al. (2020) against different temperatures of our MS stars, starting with the values of the hottest MS bin and progressively getting into cooler bins, until the WD became detectable as per our conditions in Section 4.3.1. As a result, we can determine the maximum $T_{\text{eff,MS}}$ for which a WD with given parameters can be detected, as shown in Figure 4.6. We expect a difference in the sensitivities between the FUV and NUV bands here, as WDs can produce more of an FUV excess compared to even a hot MS star, which is not strictly the case regarding the NUV, as such we expect to be able to detect a WD in the FUV next to hotter stars than is capable in the NUV.

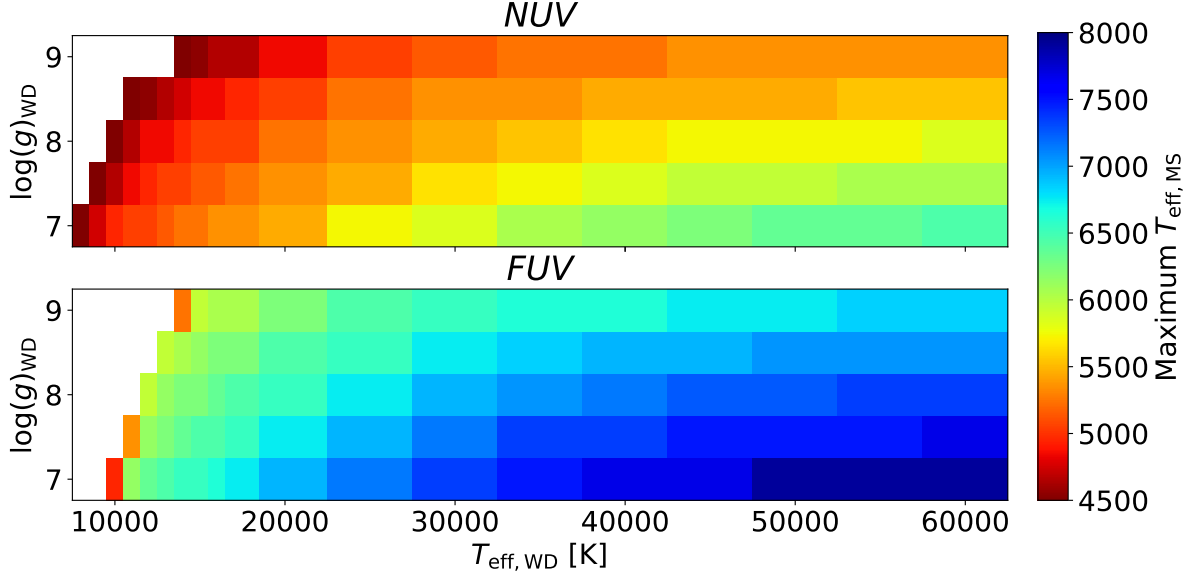


Figure 4.6: Grid showing the maximum $T_{\text{eff,MS}}$ for which a WD of given $T_{\text{eff,WD}}$ and $\log(g)$ can be detected next to, for each the *NUV* (top panel) and *FUV* (bottom panel) bands. We find that we cannot detect particularly cool WDs next to even relatively cool MS stars, though as we look at hotter WDs, we can detect them next to even relatively hot MS stars in the *FUV*, and to a lesser extent in the *NUV*.

As mentioned earlier in Section 4.3.2, as with the previous sample of Garbutt et al. (2024), we are more sensitive to lower mass ($M_{\text{WD}} \lesssim 0.6 M_{\odot}$), more luminous WDs. For a more complete catalogue, our sample could be combined with an astrometric counterpart (e.g. Shahaf et al. 2024), which are more sensitive to higher mass WDs and biased against lower mass WDs. Yet to be explored are a population of low mass WDs next to more massive MS stars, as such systems would be difficult to detect though their UV flux - as such a MS star would also dominate in the UV regime as can be seen in Figure 4.6 where the higher $T_{\text{eff,MS}}$ starts to dominate over the WD - and through astrometry, as it would be difficult to distinguish between a WD and a stellar companion next to such a luminous object.

We can check for further completeness by comparing against the *Tycho-Gaia Astrometric Solution* (TGAS) survey of Ren et al. (2020). The TGAS catalogue was constructed using *Gaia* DR1 and the Tycho-2 catalogue, with Ren et al. (2020) complementing

this with the more up-to-date photometry and parallaxes of *Gaia* DR2. Their sample of 814 DR2 sources becomes 846 DR3 sources owing to some DR2 sources being associated with multiple DR3 sources. Of these 846, 697 are found within our initial *Gaia*-*GALEX* sample. Applying our cuts from Section 4.2, we find that none are dropped from criterion (1), 1 from criterion (2), 28 from criterion (3), 4 from criterion (4), 1 from criterion (5), and 199 from criterion (6), leaving us with a sample of 464 candidates from Ren et al. (2020) that have passed our initial filters, with a further 96 not having both $\log(g)$ and T_{eff} within our range and 9 being removed by our binary cut, for a sample size of 359.

We find that 233 of these 359 (65 per cent) possible sources from Ren et al. (2020) are flagged as UV excess sources via our method, leaving 126 apparent excess sources from Ren et al. (2020) that pass all our quality cuts but are not flagged as having a UV excess. The majority of these objects are hot A/F-type MS stars (The average T_{eff} of these systems is 6600 K), which we are not sensitive to a UV excess from, except in the case of a very hot WD companion (see Figure 4.6). We suspect that these are likely not real UV excess sources, but just hot MS stars (that will be intrinsically bright at UV wavelengths) that were erroneously flagged by Ren et al. (2020).

It would be near impossible to get a genuine measure of how complete our sample is without employing a population synthesis model, however population synthesis has thus far proven unreliable for post-interaction WD binaries, particularly regarding SMT and double WD binaries (Lin et al., 2023; Nelemans et al., 2025). Parsons et al. (2016) shows in their population synthesis that we should not expect any cool WDs ($T_{\text{eff,WD}} \lesssim 15,000$ K) next to a hot MS star ($T_{\text{eff,MS}} \gtrsim 6500$ K). This is to be expected, as such a hot MS star should have evolved and become a WD itself by the time the WD has formed and cooled to this temperature. However, it is apparent that our sample becomes significantly incomplete below $T_{\text{eff,WD}} \lesssim 12,000$ K. The upcoming *Gaia* DR4 may help provide an idea of how many WD + FGK should be expected, with spectroscopy helping identify short-period systems, and astrometry helping to identify further intermediate

systems - similar to that of DR3 (see e.g. Garbutt et al. 2024). We are also limited by the lack of full-sky *FUV* coverage, as the *GALEX FUV* instrument failed before it could complete full coverage.

Whilst there is no overlap, the WD + dM survey of Rebassa-Mansergas et al. (2025) should prove to be a complementary survey to ours - as they probe a different area of the *Gaia* optical CMD (they search between the WD track and the MS track). These systems exist in a different area of parameter space, as a cooler WD can contribute significantly in optical wavelengths when in a binary with a dM star.

4.5.2 Contamination

By comparing against our SIMBAD crossmatch, we can get an approximate measure of contamination within our sample, measuring approximately 5 per cent depending on how representative the SIMBAD sub-sample is relative to the full sample. We get this number by considering 41 of the 43 eclipsing binaries as contaminants, all 10 of the ‘galaxies’ as contaminants, and the 20 young stellar objects as contaminants.

We expect a few sources of contamination within our sample beyond these kinds of objects. We expect the primary source of contamination within our sample to be systems containing an active star, as chromospheric activity can produce UV flux that would register within our detection parameters. We made an effort to reduce this source of contamination by removing the binary track, as this is where we expect a large number of these systems to lie, but there is still likely more in the sample, and removing all active stars would be counter-productive, as WD + FGK binaries can have stellar activity.

We also expect contamination from genuine multiple-star systems involving a WD, such as triple systems where there is a wide WD companion (e.g. Lagos et al. 2020a), or WD binaries that have not undergone interactions owing to having too wide of an orbit. Such systems will, of course, slip through our filters and enter our sample - as the

presence of a WD with a non-degenerate companion is exactly what our filters select for, and will require follow-up data to confirm.

Additionally, there could be contamination from foreground or background UV sources. To check for this, we checked our excess sample against the full initial *Gaia*-*GALEX* crossmatch table, searching around each source within a 5" radius. We find that 652 of our 2597 excess systems have another source within 5", with 631 of these sharing a *GALEX* object ID. We flag our sources with another detection within 5" where the other detection is unlikely to be the cause of our UV excess with a '6' in the 'Contamination' column of the supplementary table.

Of these 652 systems, we find that 533 lie across the MS and giant branch of the *Gaia* colour-magnitude diagram, and 119 lie near the WD track. In each case, we investigated the feasibility of a WD being detectable in *GALEX* at their distances. In the case of the 533 spread across the MS and giant tracks, we checked if a $\log(g) = 8$ CO core WD at 20 kK would be detectable at the given distances, and found that 509 would be detectable in either the *FUV* or *NUV*, whilst 30 would not be luminous enough to be detected in either band. We thus flag these 30 systems as being unlikely to be the cause of our observed UV excess (so are thus flagged as '6' in the 'Contamination' column of the supplementary table). As for the 509 other systems, it is unclear exactly which source is the origin of the UV excess between our flagged source and this other detection, and these are flagged as '7' in the 'Contamination' column of the supplementary table.

For the 119 systems near the WD track, we determined if these systems would be detectable by acquiring what the UV magnitudes of such a WD would be assuming a CO core WD with $\log(g) = 8$ and the *G* magnitude of the system. We find that, at their distances, all would be detectable and contribute towards a UV excess. These systems where this other source is the likely cause of our UV excess is flagged as '8' in the 'Contamination' column of the supplementary table. Interestingly, in almost all of these cases the contaminating WD has a parallax consistent with our selected UV excess

source, indicating that these are likely wide, resolved WD binary systems. We expect contamination from resolved WD binaries accounts for roughly 4 per cent of our sample.

Accounting for all sources of contamination, we estimate that our sample likely has a contamination of between 10-35 per cent, based on how representative the SIMBAD crossmatch sub-sample is, and how pessimistic we are regarding the 509 systems with another MS system within 5".

4.6 Conclusions

We have compiled a sample of 2597 WD + FGK binary candidates within 350 pc from *Gaia* by searching for a UV excess within the *GALEX* data by comparing against the MIST models corresponding to the *Gaia* parameters for the non-degenerate star. We find that 1632 of these have a low risk of being contaminants. Comparing against SIMBAD, we find 10 systems confirmed by SIMBAD to be a WD binary (or else a WD binary candidate), and a further 2 WDs or WD candidates not flagged as such within SIMBAD, but which are found as eclipsing binaries and literature has confirmed as containing a WD or candidate (Lloyd et al., 2007; Zhang et al., 2024; Zhao et al., 2024). We are able to estimate the ages of some of our systems by either comparing against clusters (Hunt & Reffert, 2024) or by looking for wide WD companions to the system (Shahaf et al., 2024), though we are able to only do this for a small number of systems within our sample.

We found that the MIST models significantly under-predict the UV flux of stars across the HRD, which we suspect is a result of the MIST models not accounting for the chromosphere. We apply polynomial corrections to these MIST models in order to bring their magnitudes more in-line with observations.

We estimate a contamination of 10-35 per cent based on our matching against SIMBAD and other nearby *GALEX* sources, depending on how representative the SIMBAD crossmatch is to our full sample. We have expanded our understanding of potential sources of contamination found through our UV excess method, with young stellar objects and wide binaries contributing more significantly as sources of contamination than expected. We cannot gather a full idea of the completeness of our sample without a better understanding of how these systems form and evolve, however we know that our sample is biased towards lower mass, hotter more luminous WDs, and we determine the maximum temperature MS star for which our method is effective for detecting WDs next

to for given WD parameters, finding that we struggle to detect any WDs in the *FUV* below a $T_{\text{eff,WD}}$ of 10,000 K regardless of the $T_{\text{eff,MS}}$ of the companion. Whilst we can detect WDs at lower $T_{\text{eff,WD}}$ s (down to ≈ 8000 K), we find that the hotter WDs are less visible in the *NUV* than in the *FUV*, with a lower minimum maximum $T_{\text{eff,MS}}$ being able to mask the WD in the *NUV*.

This sample should prove useful in finding populations of WD + FGK binaries in the local area to study binary evolution, though follow-up spectroscopic observations are required in order to confirm the presence of a WD.

Chapter 5

Conclusion

“ It’s f*cking science!
Just ask Albert Einstein,
he invented space ”

— Ninja Sex Party, *Dinosaur Laser Fight*, 2011

5.1 Future Work

Having established two catalogues of WD + FGK candidates in this thesis - a smaller sample of 206 ‘good’ candidates with measured stellar and binary parameters from Chapter 3 (*Gaia* orbits for known UV excess binaries) and a larger sample of 2597 candidates from Chapter 4 (The *Gaia-GALEX* UV Excess Sample for systems within 350 pc) with measured stellar parameters, there are a few main avenues for where this work could go next to build on these samples.

5.1.1 Follow-up Observations

Whilst the work in this thesis has established catalogues of WD + FGK binary candidates, follow-up observations will be required to confirm binarity, and to acquire binary parameters for the sources found in Chapter 4 (The *Gaia-GALEX* UV Excess Sample for systems within 350 pc). The upcoming *Gaia* Data Release (DR)4 may be of use, potentially increasing the scope of the binary catalogues of *Gaia* DR3 and providing orbital parameters for these systems, though other surveys and telescopes may be able to detect binarity through variations in radial velocities (see e.g. Parsons et al. 2023).

The presence of a WD likewise needs to be confirmed in most systems within these catalogues. *Hubble Space Telescope* (HST) spectra have confirmed the presence of a few WDs in Chapter 3 (*Gaia* orbits for known UV excess binaries), and could be used to confirm others. Alternatively, the upcoming 4MOST mission (de Jong et al., 2019; Walcher et al., 2019) has a sub-survey in which to characterise close WD binaries using 4MOST spectra to obtain effective temperatures, surface gravities, radii and masses of the binary stars, and using photometric data from the Vera C. Rubin Observatory (Ivezić et al., 2019). 4MOST will also be able to search for chemical anomalies within the spectra of stars, which can be indicative of past mass transfer (see e.g. Yamaguchi et al. 2026; Hallakoun et al. 2026).

Regarding the work of [Chapter 3 \(*Gaia* orbits for known UV excess binaries\)](#), the given spectroscopic mass estimates are all lower limits owing to the unknown inclination of these systems. This makes them imperfect as a measure of exploring the mass-period relationship. Improving this by acquiring inclinations for these systems should allow to probe this relationship more completely, allowing us to investigate the likeliest evolution channel for these systems. Acquiring rotational broadening measurements from 4MOST and WEAVE ([Jin et al., 2024](#)) spectra should allow the determination of the inclination of some of these systems (see e.g. [Masuda & Winn 2020](#); [Zhang et al. 2024](#)). This method relies on the assumption that the spin and orbit of the luminous companion are aligned in order to determine the inclination of the system - which holds true for close, tidally locked systems but it remains to be tested if this assumption holds for longer period systems. To test how frequently this assumption holds true, a good sample of systems where WD masses can be determined using both this method and through [HST](#) spectroscopic fitting should be established to see if these values are consistent. If consistent for the majority of systems, this method could then be applied to a larger sample of spectroscopically determined WD + FGK binaries (such as the spectroscopic sample of [Chapter 3 \(*Gaia* orbits for known UV excess binaries\)](#)) to determine more precise measurements for these masses. If the spin and orbital axis prove to be inconsistently aligned for intermediate period systems, then this method will unfortunately only be useful for short period systems.

There is also a dearth of WD binaries in the literature with periods in the range of 5-100 d. Shorter period systems are reasonably well-studied (e.g. [Nebot Gómez-Morán et al. 2011](#)), and there are a number of systems being found with periods beyond ~ 100 d - though there are few in this intermediate range, with [Chapter 3 \(*Gaia* orbits for known UV excess binaries\)](#) being amongst the first to identify candidates in this range. Further investigation of this period range (by e.g. 4MOST or WEAVE) might reveal more insights to these elusive systems, as currently there aren't enough systems in this

region to understand the likeliest channel to how these systems came to be - and if this dearth is owing to biases within *Gaia* DR3, or if there is a genuine lack of systems in this range signifying a genuine separation between those formed by CEE (shorter period systems, and the high-mass long period systems) and those by SMT (the lower mass, long period systems).

Another area of Mass-Period space that remains currently unexplained at the time of writing are the intermediate mass ($\sim 0.6 - 0.8 M_{\odot}$), long-period systems. It remains likely that less massive longer period systems are formed by SMT, and that the higher mass long period systems are formed by CEE at the tip of the thermally pulsing AGB phase (Belloni et al., 2024), but neither can explain these intermediate masses.

The sample of Chapter 4 (The *Gaia*-GALEX UV Excess Sample for systems within 350 pc), whilst less biased, currently lacks any binary parameters. These will be required in order to get a better idea of which binary populations are being sampled by this method. *Gaia* DR4 will hopefully expand on the binary catalogues of *Gaia* DR3, both extending to longer period systems and providing more radial velocity data in order to get more orbital period measurements.

5.1.2 Complementary Surveys

As alluded to in Sections 3.5.7 and 4.5.1, there are other surveys using different methods looking for objects similar to ours. Specifically, the astrometric sample of Shahaf et al. (2024) looks for similar systems, though because of the differences in selection criteria and the differences between their astrometric method and the UV excess method employed in this thesis, both samples are biased towards different populations of WDs - with the UV excess being biased towards lower mass and hotter WDs, and the astrometric method being biased towards more massive WDs and lower mass FGK stars, with an absence of giant stars. Thus, combining these two methods would provide a more complete sample

of WD + FGK binary candidates.

A sample of WD + dM binaries, such as that of Rebassa-Mansergas et al. (2025), likewise probes a completely different area of parameter space - as these systems should lie in a far bluer region of the *Gaia* CMD compared to WD + FGK binaries, as next to a dM a WD can contribute a significant amount of optical flux. Whilst different systems, they can be used in a similar way - as a laboratory to investigate binary physics.

5.1.3 New Surveys

The upcoming *Gaia* Data Release (DR)4 stands as an exciting way to improve upon the data used in this thesis, offering more precise measurements which should allow surveys like those found in this thesis to better constrain WD parameters. Additionally, more precise and up-to-date UV photometry would allow for better detection of WD + FGK binaries. There are a few new UV surveys planned for the coming years. The Ultraviolet (UV) EXplorer (UVEX) (Kulkarni et al., 2023) is a NASA space telescope designed as a successor to *GALEX*, and is expected to be 50-100 times more sensitive with a 2.25" resolution opposed to *GALEX*'s $\sim 5.5''$, and has a projected launch date at some point in 2030.

A larger, more uniformly selected sample could be used to test and improve models of transfer (both Common Envelope Evolution (CEE) and Stable Mass Transfer (SMT)), and thus improve models of WD binary evolution. Such a sample would need to include not just WD + FGK binaries, but WD + dM binaries and WD + A binaries. It would be somewhat challenging to apply a selection criteria that includes all of these systems, as WD + dM binaries sit in a different area of the optical CMD, and WD + A binaries are difficult to detect through either a UV excess method or by an astrometric method; as an A type star will outshine a WD even in UV wavelengths - making the UV excess method ineffective - and these stars are so massive and bright that the astrometric ‘wobble’ of

the photocentre becomes incredibly small - making the astrometric method of [Shahaf et al. \(2024\)](#) ineffective.

5.1.4 Ultimate Aims

The ultimate aim of creating catalogues of [WD](#) + FGK binary candidates such as those found in this thesis is to understand how these binaries evolve, essentially these serve as a [White Dwarf \(WD\)](#) binary pathways survey. We want to understand the ratios of these different channels, to get an understanding of how many of these we can expect to be [SNe Ia](#) or gravitational wave progenitors, and how many we expect to merge. Merged [WDs](#) have different properties to a [WD](#) that emerge from isolated stellar evolution - with more polluted spectra, and are likely to be hotter than [WDs](#) of a similar mass that evolved in isolation, owing to the energy involved in the merger. Given [WDs](#) have been used as age estimates for both the galactic disc and of the universe ([Winget et al., 1987](#); [Pitts & Tayler, 1992](#)), it is crucial to get an understanding of such [WDs](#).

5.2 Summary

This thesis has used *Gaia* [DR3](#), both in order to make improvements on previous samples of [WD](#) + FGK candidates, and to create a new volume-limited sample of candidates with hopefully fewer biases. The two samples created in this work can be seen in [Figure 5.1](#).

In [Chapter 3](#) (*Gaia* orbits for known UV excess binaries), I took three prior samples of [WD](#) + FGK binary candidates ([Parsons et al., 2016](#); [Rebassa-Mansergas et al., 2017](#); [Ren et al., 2020](#)) and matched these with *Gaia* [DR3](#). Unexpectedly, I discovered from *Gaia* photometric data that a number of these systems, all of which had been assumed to be [Main Sequence \(MS\)](#) stars, were actually giants. Matching with *Gaia* [DR3](#)'s `nss_two_body_orbit` catalogue of binaries to acquire binary parameters, I performed a fitting of the star's optical and infrared magnitudes using the *ISOCHRONES* package

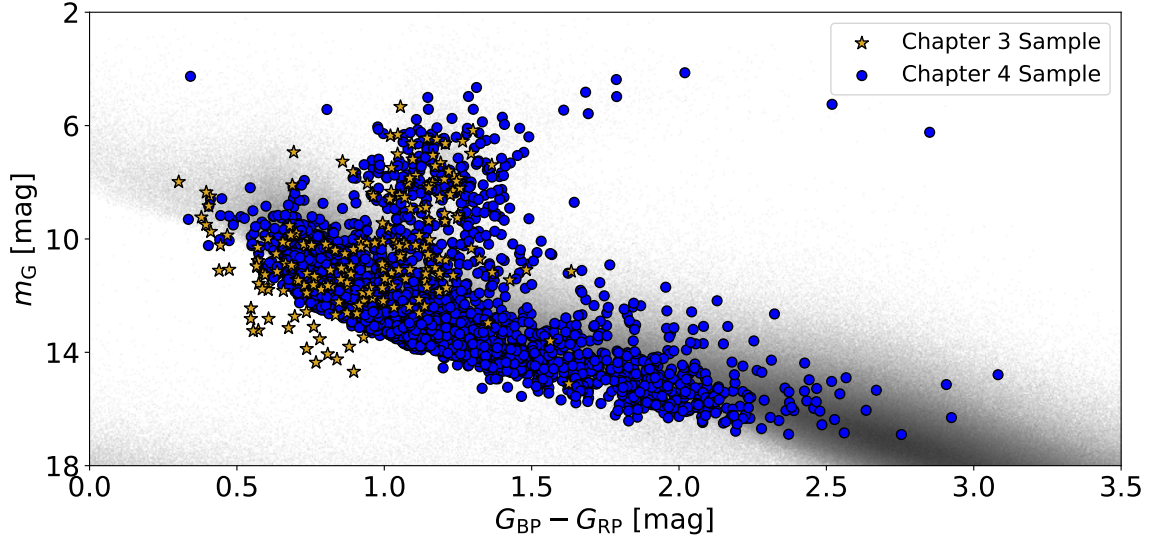


Figure 5.1: *Gaia* CMD showing both the sample of 206 WD + FGK candidates from Chapter 3 (*Gaia* orbits for known UV excess binaries) (gold stars), and the 2597 WD + FGK sample of Chapter 4 (The *Gaia*-GALEX UV Excess Sample for systems within 350 pc) (blue circles).

(Morton, 2015) (see Chapter 2 (Methodology, Techniques and Instrumentation)) using both single and double star models, discarding systems where the double star model was the better fit as WD + FGK systems should appear as a single star at these wavelengths. Using the stellar mass found through this fitting in conjunction with the methods described in Chapter 2 (Methodology, Techniques and Instrumentation), I was able to acquire WD parameters.

Prof. Odette Toloza was able to perform a fitting to *HST* spectra, and confirm the presence of a handful of WDs in the sample, finding masses with reasonable agreement to those found through our fitting. We plotted these systems in Mass-Period space (see Figure 3.8), finding a number of systems in locations that are difficult to explain by either SMT or by a conventional phase of CEE. We speculate that the very low-mass WDs with long periods are triple star systems, with the long-period high-mass WDs aiding in the investigation of Belloni et al. (2024), finding that such systems can be produced if the CEE occurs when the WD progenitor was at the tip of the thermally pulsing AGB.

Following on from this, in Chapter 4 (The *Gaia*-*GALEX* UV Excess Sample for systems within 350 pc) I establish a new sample of WD + FGK candidates based on the *Gaia*-*GALEX* crossmatch performed by Dr. Nicola Gentile Fusillo. Here, I trust the *Gaia* DR3 GSPPHOT parameters (Andrae et al., 2023) of surface gravity, effective temperature and metallicity. I match MIST models to these parameters to get the UV magnitudes of a model star sharing these parameters, though find a systematic offset between the observed UV magnitudes and those proposed by the MIST models - which I attribute to the MIST models not accounting for a chromosphere, which generates a significant amount of UV flux. After correcting for this offset, I use χ^2 minimization (see Chapter 2 (Methodology, Techniques and Instrumentation)) in order to acquire WD parameters where there was a clear excess in both the FUV and NUV - using interpolation in the event where there was only an excess in one UV band.

I then crossmatch against various external catalogues to identify the level of contamination with the sample - finding contamination from sources as varied as young stellar objects, background galaxies, and background lone WDs. I also estimate the maximum temperature WD that this method can detect next to a MS star of a given temperature.

The samples found in this thesis, both those from Chapter 3 (*Gaia* orbits for known UV excess binaries) and Chapter 4 (The *Gaia*-*GALEX* UV Excess Sample for systems within 350 pc) will be useful tools for investigating WD + FGK evolution, providing populations of various periods from Chapter 3 (*Gaia* orbits for known UV excess binaries) which should allow the probing of the past evolution of WD + FGK binaries, and a sample of WD + giant stars, which prove difficult to detect with other methods and which should serve as useful indicators to probe an otherwise unique population of WD binaries.

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Appendix A

Appendix

A.1 Supplementary Figures

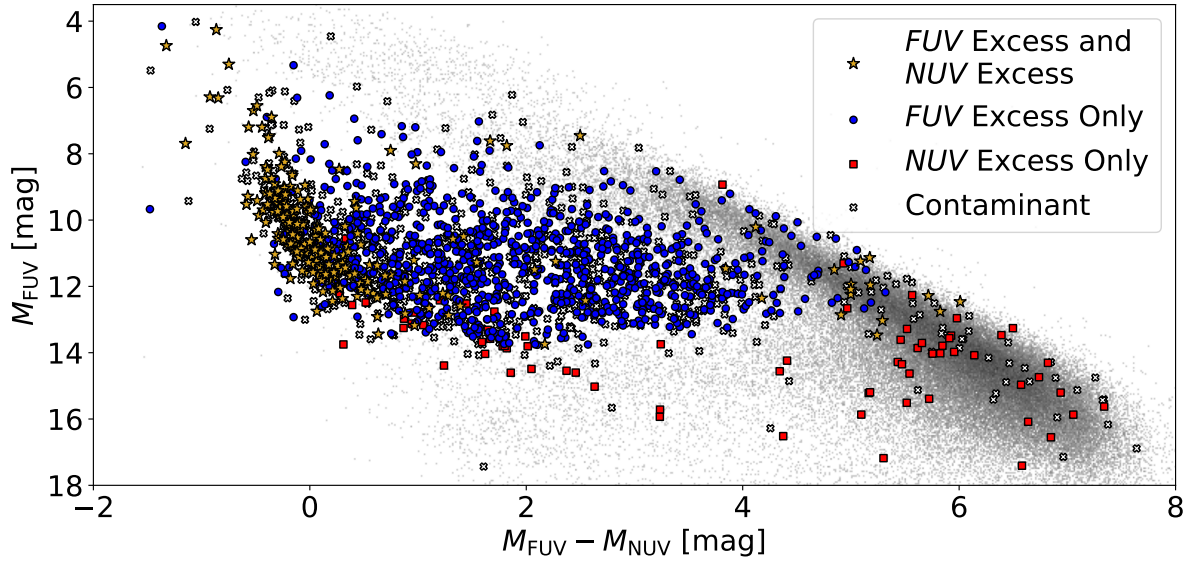


Figure A.1: UV colour magnitude diagram displaying where our excess systems lie in and UV colour space. Our systems with an excess in both UV bands are shown as golden stars, where there was only a *FUV* excess as blue circles, systems with only an *NUV* excess as red squares and likely contaminants as a white cross. These ‘Contaminants’ are flagged based on the ‘Contaminants’ column in the supplementary table.

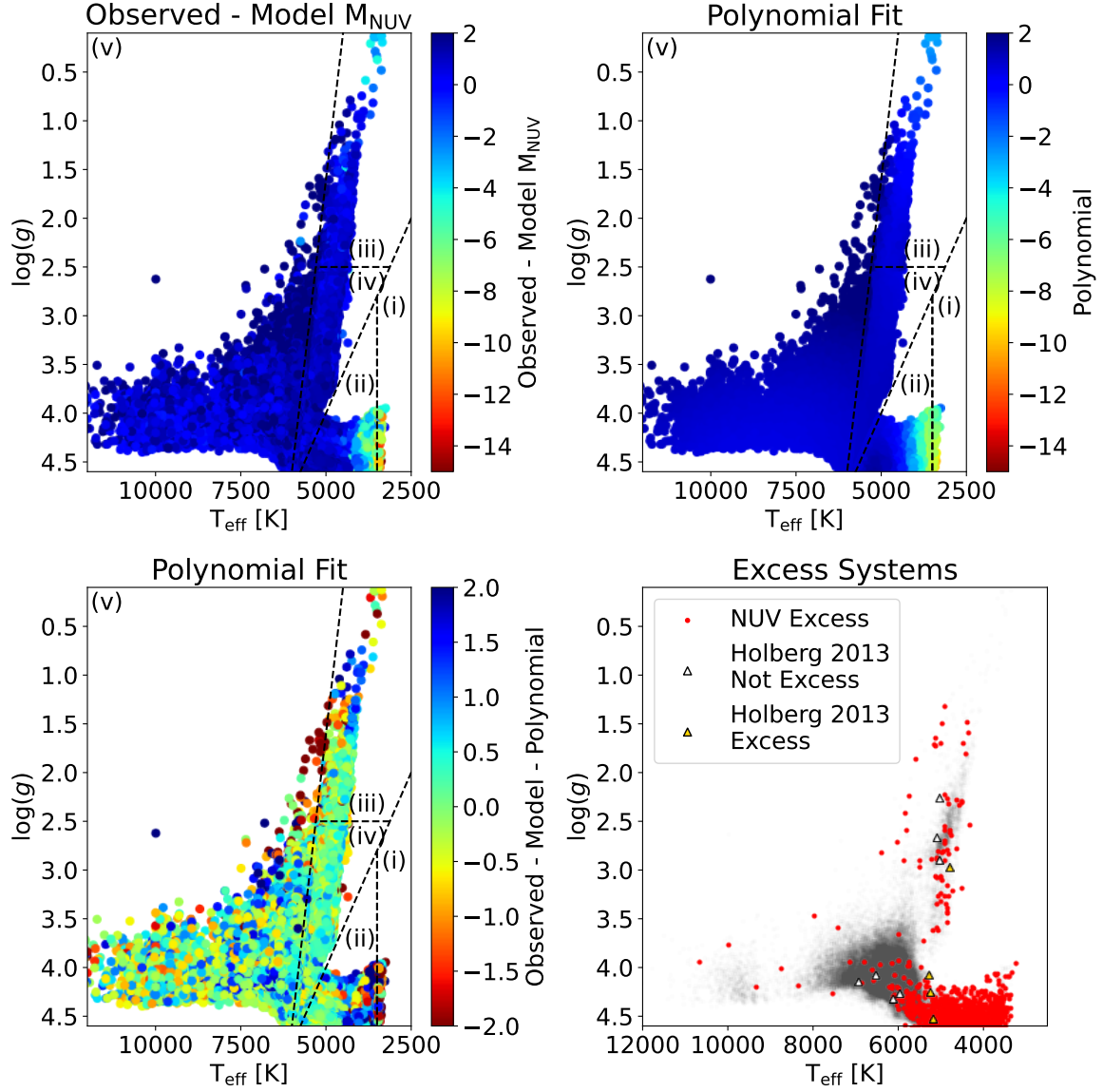


Figure A.2: Kiel diagrams of the 488,148 objects in Gaia DR3 with measured parameters, within 350 pc and with a *NUV* detection in *GALEX*. The top left panel is colour-coded by the observed, absolute de-reddened *NUV* magnitude minus the MIST model magnitude of the system as found by fitting the T_{eff} , $\log(g)$ and Fe/H of the system. The top right panel is colour-coded to show the polynomial fit to the distribution, and the bottom left shows the residuals after the polynomial corrections are subtracted. The dashed lines indicate the boundaries of the different regions where different polynomials were fit. The bottom right panel shows our systems that were flagged as an excess, with the known WD + FGK systems from Holberg et al. (2013) shown as triangles, the gold triangles where these were found as an excess in this band, and the white triangle where they were not flagged as an excess in this band.

A.2 Crossmatch Tables

Table A.1: Our candidate systems that are flagged as being potential cluster members in [Hunt & Reffert \(2024\)](#). We do not make cuts based on their probability of membership, as binary evolution can make this less straightforward (e.g. V* V471 Tau being a confirmed member of the Hyades cluster, but only having a probability of 52 per cent)

SIMBAD Main ID	Cluster	Cluster Age (Myr)	Probability (per cent)
2MASS J22131219+7332585	Collinder 471	4.8	100
CHX 18N	Chamaleon I	5.7	100
Cl* NGC 2632 JC 261	NGC 2632	346.2	57
Gaia DR2 5579241033805198976	CWNU 1169	79	90
Hen 3-545	Chamaleon I	5.7	98
Hn 23	Theia 29	18.3	100
IRAS 05271+0252	ASCC 21	6.9	100
V* Cl Tau	CWNU 1129	15.0	100
V* CV Cha	Chamaleon I	5.7	100
V* SY Cha	Chamaleon I	5.7	59
V* V471 Tau	Hyades	576.8	52
V* VZ Cha	Chamaleon I	5.7	100
[K98c] Em* 109	Collinder 471	4.8	100

Table A.2: Our SIMBAD White Dwarf crossmatch results. Here, we give their primary SIMBAD ID, their likely object type based on the literature, and the source of the classification.

SIMBAD Main ID	Object Type	Source
* 29 Dra	RS CVn (WD + K)	Hall et al. (1982); McCook & Sion (1999)
BD+08 102	Wide WD + K (Unlikely CV)	Barstow et al. (1994); Kellett et al. (1995)
CPD-65 264	WD + G	Leiner et al. (2018); Sun et al. (2024)
HD 2133	WD + F	Parsons et al. (2016); Ren et al. (2020)
HD 18131	WD + K	Hernandez et al. (2022b)
HD 90052	WD + F	Houk & Cowley (1975); Burleigh et al. (1997)
LAMOST J035557.92+432402.3	WD + MS	McCook & Sion (1999); Barstow et al. (2001)
PN A66 35	WD + G (Unlikely PN)	Vennes et al. (1995b,a)
TYC 110-755-1	WD + G	Burleigh et al. (1997); Holberg et al. (2013)
V* V471 Tau	WD + K	Ren et al. (2018)
		Frew (2008); Tyndall et al. (2013); Jacoby et al. (2021)
		Ren et al. (2020); Hernandez et al. (2022a)
		Nelson & Young (1970)

A.3 Sky Images

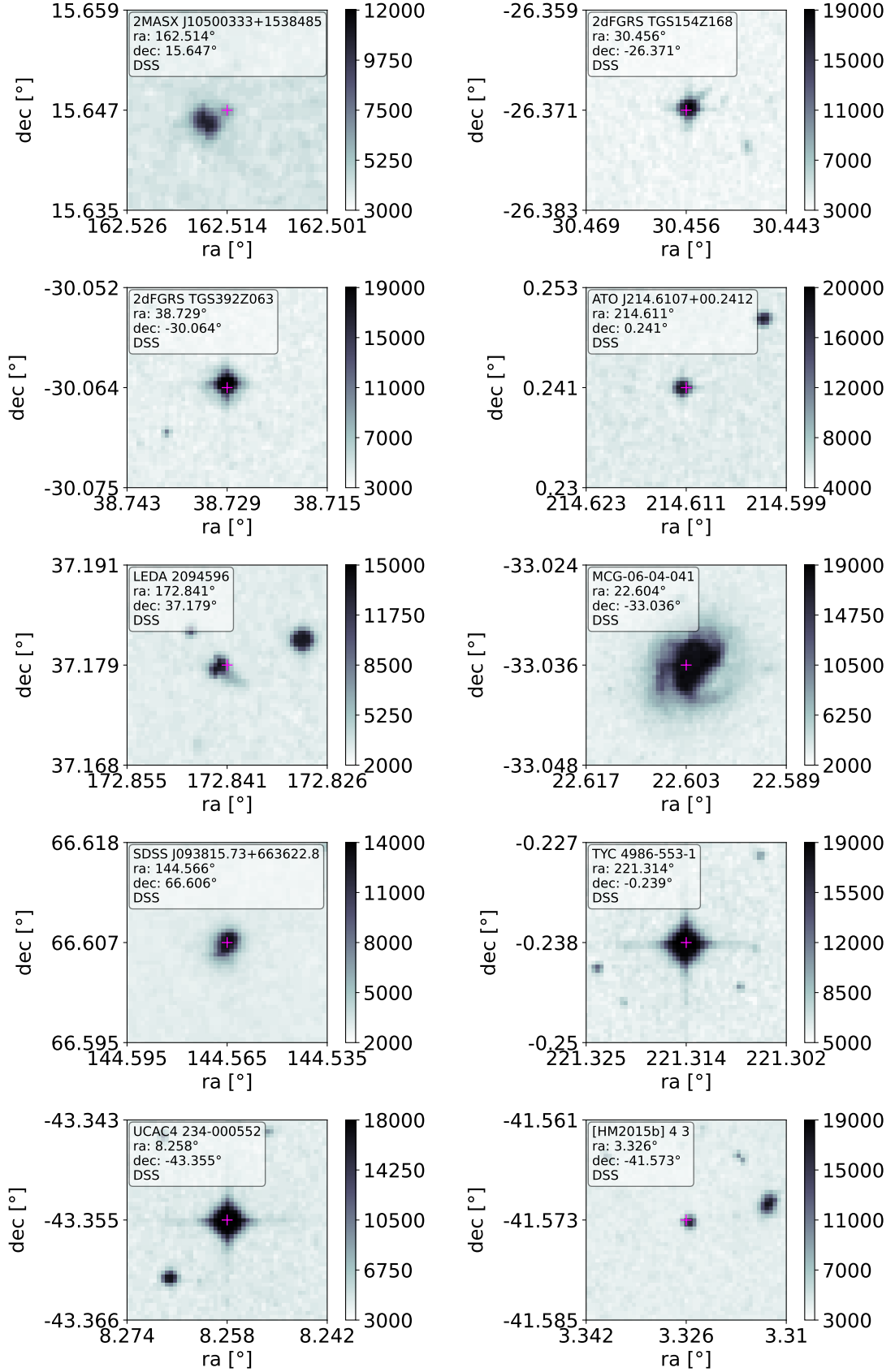


Figure A.3: Images of the different systems in our samples that were identified as galaxies in SIMBAD. Original images from DSS.

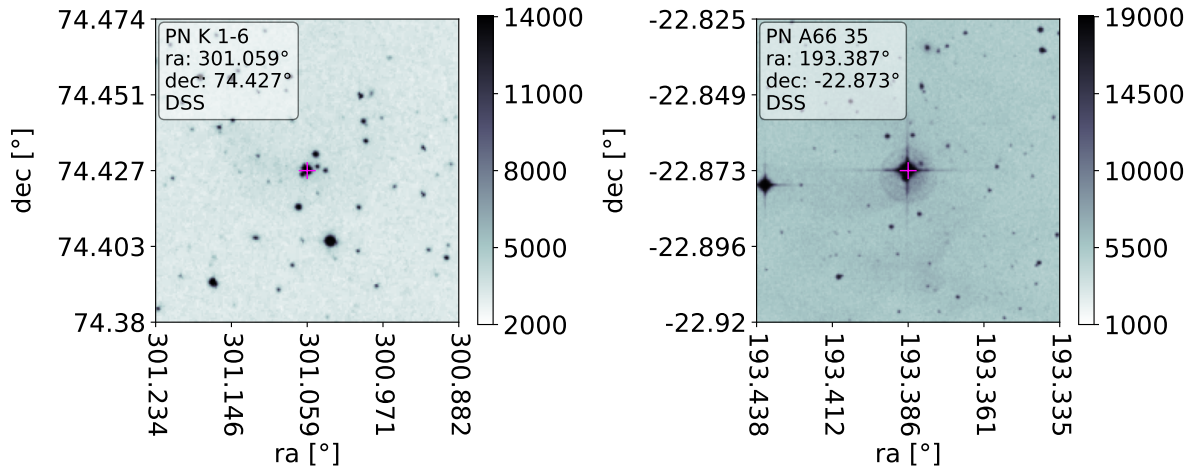


Figure A.4: Images of the two systems in our sample flagged as planetary nebulae in SIMBAD. PN A6635 appears to sit in a cloud of dust here, though as discussed in the text, it is not believed to be a planetary nebulae.

