Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **454,** 53–63 (2015) doi:10.1093/mnras/stv1913

A wide binary trigger for white dwarf pollution

Amy Bonsor[1,2]★ and Dimitri Veras[3]
[1]*Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*
[2]*School of Physics, H.H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, UK*
[3]*Department of Physics, University of Warwick, Coventry CV4 7AL, UK*

Accepted 2015 August 16. Received 2015 August 12; in original form 2015 July 15

ABSTRACT

Metal pollution in white dwarf atmospheres is commonly assumed to be a signature of remnant planetary systems. Most explanations for this pollution predict a sharp decrease in the number of polluted systems with white dwarf cooling age. Observations do not confirm this trend, and metal pollution in old (1–5 Gyr) white dwarfs is difficult to explain. We propose an alternative, time-independent mechanism to produce the white dwarf pollution. The orbit of a wide binary companion can be perturbed by Galactic tides, approaching close to the primary star for the *first* time after billions of years of evolution on the white dwarf branch. We show that such a close approach perturbs a planetary system orbiting the white dwarf, scattering planetesimals on to star-grazing orbits, in a manner that could pollute the white dwarf's atmosphere. Our estimates find that this mechanism is likely to contribute to metal pollution, alongside other mechanisms, in up to a few per cent of an observed sample of white dwarfs with wide binary companions, independent of white dwarf age. This age independence is the key difference between this wide binary mechanism and others mechanisms suggested in the literature to explain white dwarf pollution. Current observational samples are not large enough to assess whether this mechanism makes a significant contribution to the population of polluted white dwarfs, for which better constraints on the wide binary population are required, such as those that will be obtained in the near future with *Gaia*.

Key words: Oort Cloud – planets and satellites: dynamical evolution and stability – planet–star interactions – stars: AGB and post-AGB – stars: evolution – stars: kinematics and dynamics.

1 INTRODUCTION

Elements heavier than helium sink rapidly in the atmospheres of white dwarfs, where sinking time-scales are on the order of days to weeks (DA white dwarfs) and 10^4–10^6 yr (DB white dwarfs; Koester & Wilken 2006) or see fig. 1 of Wyatt et al. (2014). Observations of emission lines from metallic species in the atmospheres of white dwarfs (e.g. Koester, Provencal & Shipman 1997; Zuckerman et al. 2003; Melis et al. 2010), therefore, suggest the recent accretion of the observed material. Accretion from the interstellar medium was ruled out by Farihi et al. (2010), Aannestad et al. (1993), Jura (2006), Kilic & Redfield (2007), and Barstow et al. (2014). These observations are thought to indicate the accretion of planetary material (e.g. Alcock, Fristrom & Siegelman 1986; Debes & Sigurdsson 2002; Jura 2003, 2008; Kilic et al. 2006), in at least 25 per cent (Zuckerman et al. 2003, 2010), but maybe up to 50 per cent (Koester, Gänsicke & Farihi 2014) of white dwarfs. Dusty and/or gaseous discs, very close ($r < R_\odot$) to a subset of these polluted white dwarfs may be indicative of the accreting material (e.g. Gänsicke et al. 2006; Kilic et al. 2006; Gänsicke, Marsh & Southworth 2007; Jura et al. 2007; von Hippel et al. 2007). The composition of the accreted material, when analysed in detail supports the planetary material hypothesis (e.g. Klein et al. 2010, 2011; Gänsicke et al. 2012).

Planetary systems are common on the main sequence, and throughout the Milky Way they are the rule, not the exception (Cassan et al. 2012). Observations with HARPS suggest that at least 50 per cent of solar-type stars harbour at least one planet with a period less than 100 d (Mayor et al. 2011), whilst *Herschel* found that at least 20 per cent of FGK stars have a detectable debris disc (Eiroa et al. 2013). Although close-in (<1–5 au) planets may be swallowed by the expanding giant's envelope (Villaver & Livio 2007, 2009; Mustill & Villaver 2012; Adams & Bloch 2013; Villaver et al. 2014), there is no evidence that all outer planetary systems are destroyed (e.g. Jura 2004; Bonsor & Wyatt 2010). Dynamical instabilities in the outer planetary system, induced following stellar mass-loss (e.g. Debes & Sigurdsson 2002; Veras et al. 2011, 2013; Veras & Tout

★ E-mail: amy.bonsor@gmail.com

© 2015 The Authors
Published by Oxford University Press on behalf of the Royal Astronomical Society

2012; Veras & Wyatt 2012; Voyatzis et al. 2013; Mustill, Veras & Villaver 2014; Veras & Gänsicke 2015), may scatter asteroids or comets on to star-grazing orbits (Bonsor, Mustill & Wyatt 2011; Bonsor & Wyatt 2012; Debes, Walsh & Stark 2012; Frewen & Hansen 2014), where they are tidally disrupted and accreted on to the star (e.g. Graham et al. 1990; Jura 2003, 2008; Bear & Soker 2013; Veras et al. 2014b, 2015c).

Given a sufficiently massive planetesimal belt, it has been shown that such a theory can explain the observed metal pollution (Bonsor et al. 2011; Debes et al. 2012; Frewen & Hansen 2014). However, a steep decrease in the mass of asteroids/comets scattered on to star-grazing orbits with time after the formation of the white dwarf, is predicted (Bonsor et al. 2011; Debes et al. 2012). This finding would correspond to a steep decrease in the level of pollution (or fraction of systems with pollution), as a function of time. Although late time instabilities may be induced in multiplanet systems (Veras et al. 2013; Mustill et al. 2014; Veras & Gänsicke 2015), the frequency of these will always be less than those around young white dwarfs.

Observationally there is no evidence that there are fewer, old polluted white dwarfs, nor that the level of pollution decreases with white dwarf cooling age (Koester et al. 2014; Wyatt et al. 2014). Even the archetypal polluted white dwarf, van Maanen's star (van Maanen 1920), has an effective temperature of 6220 K, or cooling age of ∼3 Gyr (Sion et al. 2009), and there are many further observations of polluted, old, white dwarfs ($T_{\rm eff}$ < 8000 K, equivalent to cooling ages of up to 5 Gyr; Farihi et al. 2011; Koester et al. 2011). Instabilities induced following stellar mass-loss struggle to explain pollution for white dwarfs with cooling ages of Gyr (Debes & Sigurdsson 2002; Bonsor et al. 2011; Debes et al. 2012). Alternative explanations for the pollution in these systems have been suggested, including stellar encounters (Farihi et al. 2011), or a relationship with magnetic fields (Hollands, Gänsicke & Koester 2015). Others, such as exo-Oort cloud comet impacts (Veras, Shannon & Gänsicke 2014d; Stone, Metzger & Loeb 2015) and volatile sublimation of minor bodies in planet-less systems (Veras et al. 2015a), have largely been ruled out.

Here, we suggest an alternative explanation. It has been shown for main-sequence planetary systems, that whilst in general wide (a > 1000 au) binary companions do not influence the dynamics of the planetary system, the orbit of the binary varies due to Galactic tides. During periods of 'close' pericentre passage, the binary may excite the eccentricities of planets, even ejecting them (Kaib, Raymond & Duncan 2013). The increased eccentricity of exoplanets in systems with wide binary companions has been confirmed by observations (Kaib et al. 2013). Here, we propose that the same scenario could be applied to white dwarf planetary systems. If the white dwarf is orbited by a wide binary companion, the planetary system may remain unperturbed for billions of years, before Galactic tides alter the orbit of the companion such that it induces dynamical instabilities in the planetary system. These instabilities can lead to material being scattered on to star-grazing orbits and accreted on to the white dwarf, such that we observe pollution in the white dwarf's atmosphere. This process has the advantage of being independent of the age of the white dwarf, although it depends critically on the population of wide binaries orbiting white dwarfs.

The population of wide (>1000 au) binaries is difficult to characterize, in general. Common proper motions indicate that two stars may be related (e.g. Lépine & Bongiorno 2007; Makarov, Zacharias & Hennessy 2008), but follow-up parallax and radial velocity observations are required to determine whether they are bound. Wide binaries are, therefore, likely to be significantly more common than determined observationally. Theoretical models predict a wide binary fraction of 1–30 per cent, with $10^3 < a < 0.1$pc (Kouwenhoven et al. 2010), whilst observations of solar-type stars (Lépine & Bongiorno 2007; Raghavan et al. 2010) find a fraction of 9.5 or 11.5 per cent, and observations of field white dwarfs yield a wide binary fraction of 22 per cent (Farihi, Becklin & Zuckerman 2005). There are, however, very few white dwarfs with known wide binary companions that have been searched for pollution, and many surveys for pollution have focused on apparently single white dwarfs. Zuckerman (2014) present a sample of 17 white dwarfs with companions separated by more than 1000 au, searched for Ca II with Keck/VLT and find that five are polluted. We note here that white dwarfs in close binaries may be polluted by interactions with the stellar wind of the companion, as discussed in (e.g. Zuckerman et al. 2003; Zuckerman 2014), and for this reason we focus on 'wide' binaries. Fig. 8 of Veras & Tout (2012) shows that the boundary between 'close' and 'wide' occurs at tens of au.

In this paper, we illustrate the manner in which a wide binary companion could lead to pollution in a white dwarf. This mechanism is likely to be just one of many that lead to pollution. The critical difference of this mechanism is the absence of any dependence on white dwarf cooling age. Section 2 shows how a wide binary's orbit can be altered by Galactic tides, such that a close approach occurs between the secondary and a planetary system orbiting the primary (white dwarf). Section 3 presents simulations that show how this close approach can lead to planetesimals scattered on to star-grazing orbits, a pre-requisite for pollution. In Section 4, we estimate the fraction of white dwarfs with wide binary companions where pollution might occur, which is compared to observations in Section 5. In Sections 6 and 7, we discuss our results and present our conclusions.

2 THE CHANGE IN ORBIT OF A WIDE BINARY DUE TO THE GALACTIC TIDE

We first illustrate the manner in which the Galactic tide can change the orbit of a wide binary. Above a critical separation, the Galactic field strength is different for the two components of the binary, such that their orbit evolves. Analytically the effect of the Galactic tide on the binary's orbit can be understood through the equations of motion for the binary's orbital parameters. Although we are unaware of a complete analytic solution to these equations (1)–(4), numerical solutions can be used to explore the phase space and help us to understand the evolution of the binary's orbit.

2.1 Equations of motion

As the majority of observed polluted white dwarfs are nearby (e.g. within 0.1 kpc; Holberg et al. 2008), we restrict ourselves to the Solar neighbourhood, which we assume resides within 8 kpc of the Galactic Centre. This restriction allows us to neglect planar Galactic tides (see fig. 2 of Veras & Evans 2013b), which represents a widely used simplification (Heisler & Tremaine 1986; Matese & Whitman 1989, 1992; Matese et al. 1995; Breiter, Dybczynski & Elipe 1996; Brasser 2001; Breiter & Ratajczak 2005). Further, we consider only bound binary systems. Boundedness effectively equates to adiabaticity in the Galactic tidal regime because no escape can occur in the adibatic regime (Veras & Evans 2013b) and the non-adibatic limit is close to the system's Hill ellipsoid (Veras et al. 2014a). For very wide binaries ($a_{\rm b} > > 10^5$ au) adiabaticity is no longer a good approximation (shown by fig. 3 of Veras & Evans 2013a) and the full equations of motion describing this regime are shown in column 5 of table 1 in Veras et al. (2014a).

Here, we consider the adiabatic regime. Consequently we can, by considering vertical tides alone and using the perturbed two-body problem, derive the equations of motion for the orbital elements of the binary (as shown in Veras & Evans 2013b); semimajor axis, $a_{\rm b}$, mean motion, $n_{\rm b}$, eccentricity, $e_{\rm b}$, inclination of the binary orbital plane to the Galactic plane, $i_{\rm b}$, argument of pericentre, $\omega_{\rm b}$:

$$\frac{{\rm d}n_{\rm b}}{{\rm d}t} = 0 \tag{1}$$

$$n_{\rm b}\frac{{\rm d}e_{\rm b}}{{\rm d}t} = -\frac{5e_{\rm b}\sqrt{1-e_{\rm b}^2}}{2}\cos\omega_{\rm b}\sin\omega_{\rm b}\sin^2 i_{\rm b}\Upsilon_{zz} \tag{2}$$

$$n_{\rm b}\frac{{\rm d}i_{\rm b}}{{\rm d}t} = \frac{5e_{\rm b}^2\sin 2\omega_{\rm b}\sin 2i_{\rm b}}{8\sqrt{1-e_{\rm b}^2}}\Upsilon_{zz} \tag{3}$$

$$n_{\rm b}\frac{{\rm d}\omega_{\rm b}}{{\rm d}t} = \frac{5\sin^2\omega_{\rm b}\left(\sin^2 i_{\rm b} - e_{\rm b}^2\right) - \left(1-e_{\rm b}^2\right)}{2\sqrt{1-e_{\rm b}^2}}\Upsilon_{zz}. \tag{4}$$

The variable Υ_{zz} is determined by the Galactic model used, and contains information about the matter density and gravitational potential. Here, we use the disc component of the three-component model of Veras et al. (2014a). Because we fix the distance from the Galactic Centre at 8 kpc, we also fix $\Upsilon_{zz} = -5.352 \times 10^{-30}\,{\rm s}^{-2}$.

2.2 An example binary

Although we are unaware of a complete analytic solution to equations (1)–(4), we can obtain numerical solutions that enable us to follow the evolution of example orbits. There are several key properties of the evolution of binary orbits under the influence of the Galactic tide. Of particular relevance to this work is the evolution of the binary's semimajor axis and eccentricity. The semimajor axis remains constant (equation 1), under the adiabatic approximation of these equations. The eccentricity evolves periodically, with a time period and amplitude that depend on the initial conditions of the binary's orbit, as well as the strength of the Galactic tide (Υ_{zz}). If a binary's orbit is to perturb the primary's planetary system, we are interested in the maximum eccentricity that its orbit reaches and the times between eccentricity peaks. Thus, we focus on these two parameters in the following sections.

First, in order to illustrate our proposed scenario, let us consider, for example, a 1 $M_\odot$ binary companion orbiting a 1$M_\odot$ primary, in the solar neighbourhood ($R = 8$ kpc), with a semimajor axis of 3000 au, inclined to the Galactic plane by 80°. We gave the binary an initial eccentricity of $e_0 = 0.2$, and a range of initial arguments of pericentre ($\omega_0 = 5°, 40°, 90°, 160°$) and followed the evolution of the binary's eccentricity, shown in the top panel Fig. 1. The eccentricity of this binary's orbit evolves on time periods that are significantly longer than the main-sequence lifetimes of the stars, or even the age of the Universe. Therefore, if the binary starts at low eccentricity, as we assume, it remains at low eccentricity throughout the primary's main-sequence lifetime.

We then consider the fate of this binary system, as the primary becomes a white dwarf. So far, the primary's planetary system is relatively unperturbed by the binary companion. By using a typical mass-loss prescription,[1] the primary becomes a white dwarf of mass 0.52 $M_\odot$ (see caption of fig. 4 of Veras et al. 2013). At this semimajor axis mass-loss is likely to be non-adiabatic (see for example fig. 3 of Veras et al. 2014a), thus the exact expansion of the binary's orbit is difficult to predict (Veras et al. 2011). We, therefore, make a reasonable assumption that the binary's orbit expands by a factor of 3 to $a_{\rm b} = 9000$ au. Both the reduction in mass of the binary and the increase in semimajor axis of the binary, increase the ability of Galactic tides to change the binary's orbit. As is shown in the bottom panel of Fig. 1, the binary's eccentricity now evolves on 'shorter' time-scales, several rather than tens of Gyr. Thus, with our assumption that the binary's orbit starts the white dwarf phase with an eccentricity of $e_0 = 0.2$, depending on ω_0, it evolves to its maximum eccentricity (minimum pericentre) within 3–7 Gyr. Approaching the primary at a distance of closest approach of around 150 au, the binary is likely to perturb the primary's planetary system. It is these perturbations that we invoke for their ability to produce polluted white dwarfs, particularly at late times.

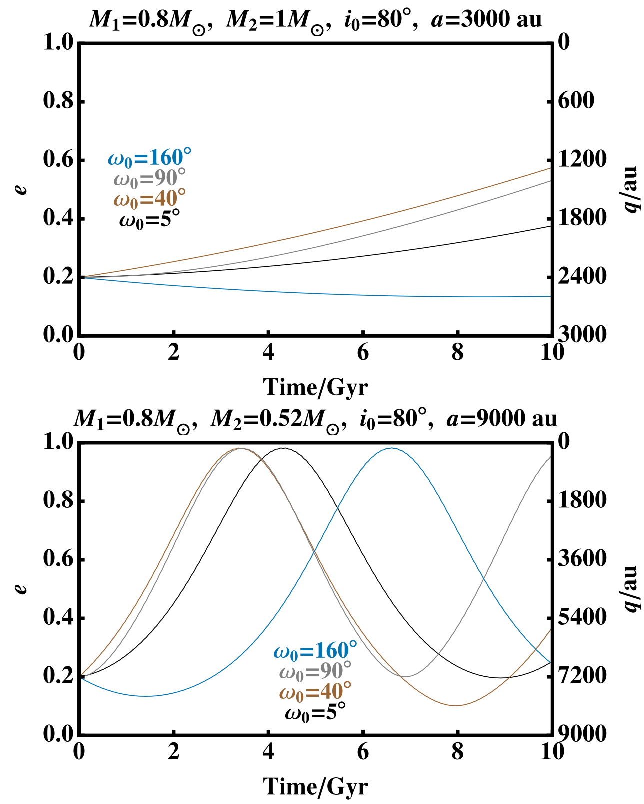

Figure 1. The change in orbital parameters due to Galactic tides and stellar evolution, for several example binaries. The top panel represents the primary on the main sequence and the bottom panel, once the primary has evolved to become a white dwarf. Tides can produce extreme eccentricity oscillations during the white dwarf phase which do not occur along the main sequence, thereby triggering planetary scattering which can ultimately lead to white dwarf pollution. Assumed in these plots is that the binary orbit expands non-adiabatically by a factor of 3 due to mass-loss from the secondary star M_2.

[1] The SSE code (Hurley, Pols & Tout 2000) applies Reimer's mass-loss (Kudritzki & Reimers 1978) at early evolutionary stages, but during the AGB it applies the semi-empirical mass-loss rate of Vassiliadis & Wood (1993), reaching a maximum during the superwind of $1.36 \times 10^9 (L_*/{\rm L}_\odot)\,{\rm M}_\odot\,{\rm yr}^{-1}$, where L_* is the stellar luminosity.

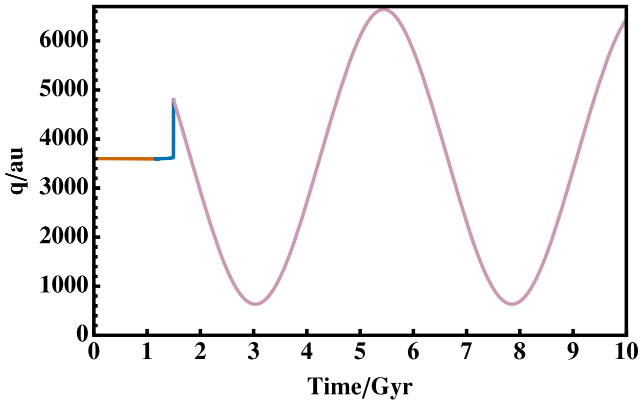

Figure 2. A demonstration of how the first close approach in a binary system can occur during the white dwarf phase. Plotted is the self-consistent pericentre distance evolution of one particular binary system through all phases of stellar evolution. The initial binary parameters are: $M_1 = 2\,M_\odot$, $M_2 = 1\,M_\odot$, $e_b = 0.1$, $a_b = 4000$ au, $i_b = 110°$, $\omega_b = 0°$. The red, blue and purple curves represent the main sequence, giant branch, and white dwarf phases of evolution, respectively. Adiabatic Galactic tidal equations are used for the main sequence and white dwarf phases; the full non-adiabatic equations for both tides and mass-loss are used along giant branch phases, with $f_0 = 150°$.

2.2.1 *Including mass-loss*

Fig. 1 integrates equations (1)–(4) for the main sequence and the white dwarf phases separately. It is possible to integrate these equations self-consistently, if a formulation for stellar mass-loss is included. However, it is computationally intensive and therefore, we only perform this calculation for one example system. Using the stellar evolution prescription of Hurley et al. (2000), coupled with *N*-body integrations, as in Veras et al. (2011), Fig. 2 shows the evolution of the pericentre of a binary orbit that starts with a $2\,M_\odot$ and a $1\,M_\odot$ planet on an orbit with $a_b = 4000$ au, but where the $2\,M_\odot$ primary evolves to become a white dwarf of mass $0.64\,M_\odot$. The same behaviour as in Fig. 1 is seen. The binary's orbit is not perturbed significantly during the main-sequence evolution, but undergoes long-period oscillations once the star becomes a white dwarf.

The mass-loss is modelled to be isotropic, which represents an excellent approximation to reality (Veras, Hadjidemetriou & Tout 2013). In this case, the pericentre can never decrease during giant branch mass-loss (equation 21 of Veras et al. 2011).

3 THE POLLUTION OF THE WHITE DWARF

We have shown that Galactic tides can perturb orbits such that a secondary companion approaches close to any planetary system orbiting the primary (white dwarf). In this section, we present simulations that illustrate how the close approach of the secondary could perturb the planetary system orbiting the white dwarf in such a manner that planetesimals are scattered on to star-grazing orbits. For the purpose of this work, we consider such scattering sufficient to produce white dwarf pollution, see Section 6 for a discussion of this assumption. These simulations are intended as a proof of concept, rather than a detailed analysis.

3.1 Details of our simulations

Clearly, the parameter space available to investigate, both in terms of the diversity of planetary system architectures and binary orbits, is enormous. We can only investigate example systems. We, therefore, consider a binary in which a $1\,M_\odot$ primary is orbited by a companion of mass $0.8\,M_\odot$. The $1\,M_\odot$ primary evolves to become a $0.52\,M_\odot$ white dwarf (Veras et al. 2013). $0.8\,M_\odot$ represents a typical value for a main-sequence stellar mass (Parravano, McKee & Hollenbach 2011), and such stars will remain on the main sequence for the current age of the Universe (∼14 Gyr).

The primary is orbited by a very simplistic planetary system with one planet and one planetesimal belt or debris disc, similar to Neptune and the Kuiper belt in our Solar system. The presence of both the planet and planetesimals means that perturbations to the orbit of the planet can lead to planetesimals being scattered on to star-grazing orbits (Bonsor et al. 2011; Debes et al. 2012). In addition, the binary companion can perturb planetesimals directly on to star-grazing orbits (e.g. Marzari et al. 2005). We fix the plane of the planetary and binary orbits to be the same. We fix the planet's semimajor axis at 30 au, which mimics Neptune's semimajor axis, and the planetesimal belt runs from 30–50 au. We assume that at such a small orbital distance stellar mass-loss is adiabatic, such that the white dwarf is orbited by a planet at 60 au and belt running from 60–100 au. We neglect the potentially destructive effects of YORP spin-up on the planetesimals (Veras, Jacobson & Gänsicke 2014c) and the potentially significant movement of these asteroids due to the Yarkovsky effect from giant branch stellar evolution (Veras, Eggl & Gänsicke 2015b). These effects would have a greater influence on an exo-asteroid belt located within 10 au than an exo-Kuiper belt located at several tens of au.

Our simulations are run using the MERCURY *N*-body integrator, RADAU (Chambers 1999). We track particles that are scattered close to the star. It is these particles that we assume are tidally disrupted and pollute the white dwarf. The RADAU integrator is used in order to track the evolution of these particles to small pericentre, in a manner that the symplectic integrator cannot. However, in order to limit the runtime for our simulations, we only track particles as close in as 0.1 au. We consider the particles that are scattered interior to 0.1 au to be representative of the population scattered on to star-grazing orbits where they would be disrupted, more likely to occur when $r < \sim R_\odot$ (Veras et al. 2014b). Given that our purpose is to illustrate the feasibility of this mechanism, we consider this assumption to be sufficient. Our choice merely means that we overestimate the population scattered on to star-grazing orbits, but do so in a consistent manner in all our simulations, thereby removing comparison inconsistencies between simulations.

We use our simulations as a tool to investigate the binary orbits that perturb the planetary system and scatter particles on to star-grazing orbits. Therefore, we focus on short integrations (10–100 binary orbits) for which the binary orbit is fixed and does not evolve due to the Galactic tide. These integrations can represent the evolution of the planetary system directly following the binary's evolution on to the orbit considered.

The exact orbits of the planet and planetesimals will clearly evolve with time and the evolution of the binary's orbit. It is not possible to consider all possible evolutionary paths. Instead, we investigate the increase in the scattering of planetesimals on to star-grazing orbits in comparison with a simulation in which the binary is not present. Although this comparison may not always mimic the potential effects of an excited planetesimal belt, or scattered disc, it illustrates clearly the perturbative effect of the binary. We start our planetesimals with orbits that are initially unperturbed by the planet and have semimajor axes, eccentricities, inclinations, longitudes of pericentre, longitudes of ascending nodes and mean anomalies, which are randomly drawn from uniform distributions with ranges

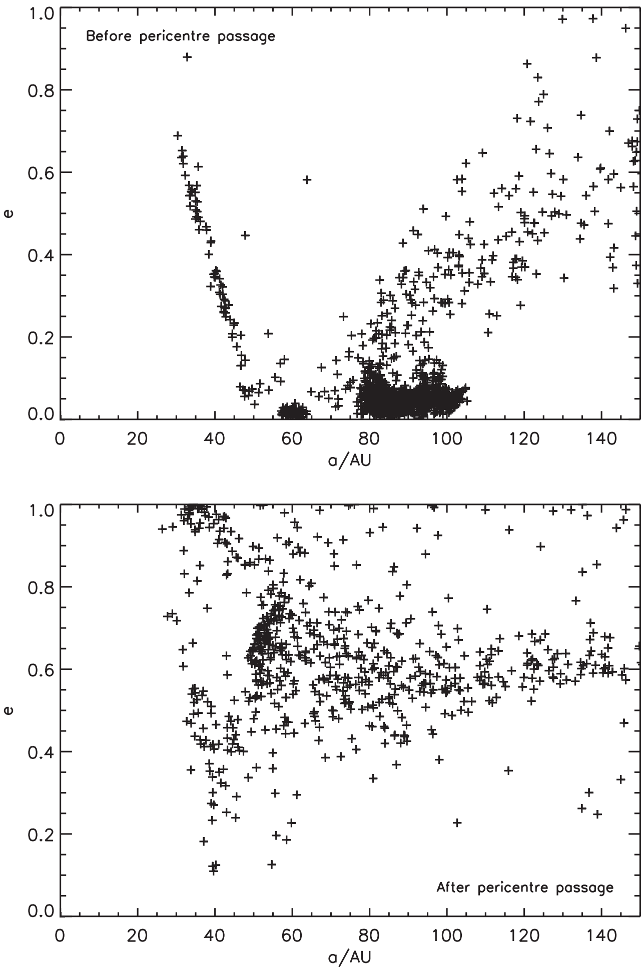

Figure 3. The semimajor axis, eccentricity distribution of planetesimals orbiting the white dwarf, prior and following the pericentre passage of a wide binary companion with $e_{\rm b} = 0.99$. This is the same system as shown in the bottom panel of Fig. 1. This figure demonstrates that despite being dynamically excited, an exo-Kuiper belt largely survives stellar evolution of a primary star with a wide-orbit companion.

of $60 < a < 100$ au, $0 < e < 0.02$, $0 < i < 1^\circ$ and $0^\circ < \lambda$, Ω, $M < 360^\circ$.

3.2 An example system

The aim of this section is to illustrate the manner in which the change in orbit of a binary due to Galactic tides can lead to the pollution of a white dwarf, even a white dwarf with a cooling age of Gyr or longer. We consider the example binary system shown in Fig 1. The binary companion orbits at $a_{\rm b} = 3000$ au and whilst it is on the main sequence has its eccentricity perturbed very little by the Galactic tide, up to an absolute maximum of $e_{\rm b} = 0.6$, from $e_{\rm b} = 0.2$ initially, during a long main-sequence lifetime of 10 Gyr. Even if the binary remains on an orbit with $e_{\rm b} = 0.6$ for 900 Myr, a typical main-sequence lifetime, an outer belt survives orbiting the primary star. In fact, our test simulation finds that more than 60 per cent of the original belt remain on stable orbits. Given that Fig. 1 shows that the binary's orbit evolves and will only be on such an eccentric orbit for time-scales significantly shorter than the primary's full main-sequence lifetime. Thus, in this example, we

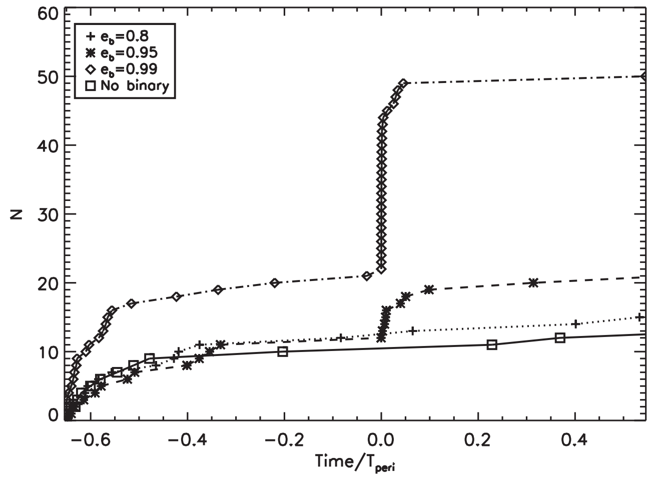

Figure 4. Our example white dwarf planetary system, orbited by a binary companion with $a_{\rm b} = 9000$ au (shown in Figs 1 and 3). The number of particles (N) that hit the star, as a function of time, in units of the binary's orbit period, with $t = 0$, occurring at pericentre. The high binary eccentricity induced by the Galactic tide increase the number of planetesimal collisions with the white dwarf.

show that a planetary system can survive the star's main-sequence lifetime without being perturbed unduly by its binary companion.

Once the primary star in this example binary evolves to become a white dwarf, the orbits of the binary and the primary's planetary system expand, for the planetary system adiabatically, but for the binary non-adiabatically. As above, we estimate that the binary's orbit moves to $a_{\rm b} = 9000$ au and consider the perturbations that it now makes on the primary's planetary system, that has expanded adiabatically by a factor of 2 (belt is now at about 60–100 au). The binary's orbit is now perturbed by the Galactic tides, evolving up to an eccentricity of 0.978 ($q \sim 200$ au) after several Gyr of evolution on the white dwarf branch. As the binary's eccentricity increases, so does its influence on the planetary system, particularly during pericentre passages. Fig. 3 shows the effect on our example planetary system of a binary with eccentricity, $e_{\rm b} = 0.99$. Fig. 3 shows that prior to the binary's pericentre passage, the planetary system is relatively undisturbed, but that following its pericentre passage the planet and many planetesimals have been scattered. As discussed above, the scattered planetesimals have the potential to pollute a white dwarf. Fig. 4 shows the number of planetesimals scattered on to star-grazing orbits following a pericentre passage by a binary on orbits with various eccentricities. For binary eccentricities above 0.8, significantly more planetesimals are scattered on to star-grazing orbits than without the presence of the binary. If we refer back to Fig. 1, depending on the exact parameters of the binary's orbit, the binary's eccentricity could be increased from 0.2 to above 0.8 between 2 and 6 Gyr after the start of the white dwarf phase. In this manner we illustrate a mechanism that could lead to the pollution of old white dwarfs.

3.3 A brief investigation of the parameter space

The above section illustrated one example system in which white dwarf pollution could occur in white dwarfs with cooling ages of Gyr. Clearly, the parameter space of binary orbits is huge and this mechanism will not work for all of them. A detailed investigation of the entire parameter space is beyond the scope of this work, and not necessary to illustrate the potential of this mechanism. Instead,

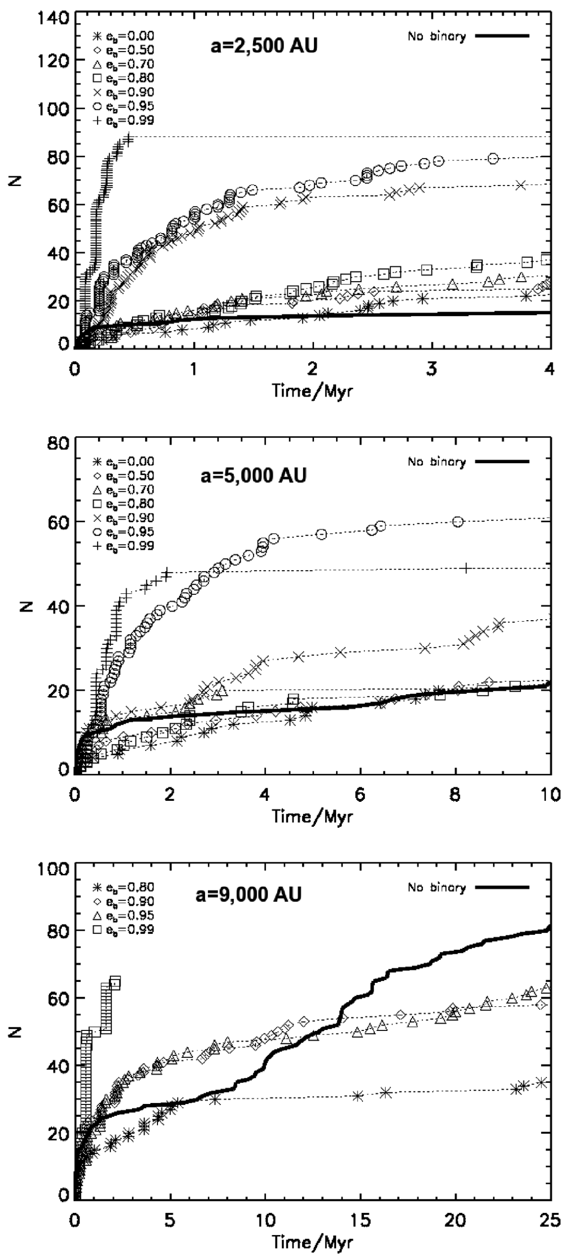

Figure 5. The number of particles (N) scattered on to star-grazing orbits as a function of time, for $a_b = 2500$ au (top), $a_b = 5000$ au (middle) and $a_b = 9000$ au (bottom). The planet is ejected for $e_b = 0.99$, $a_b = 9000$ au after 0.5 Myr, hence the scattering stops. This figure demonstrates that as the binary's orbit evolves to high eccentricity, the rate at which particles are scattered inwards increases significantly.

we perform a small additional suite of N-body simulations in order to show that there are many binary orbits for which this mechanism could work. We focus here on the white dwarf phase only.

We consider binary companions with semimajor axes of $a_b = 2500$ au, $a_b = 5000$ au and $a_b = 9000$ au. The eccentricity of the binary companion is varied, but fixed throughout each individual simulation. Fig. 5 shows the number of planetesimals scattered on to star-grazing orbits as a function of time. The pericentre passages of the binary are evident from the increase in the scattering rate, creating sawtooth-like profiles. As noted in Section 3 these numbers must be compared to the simulation with

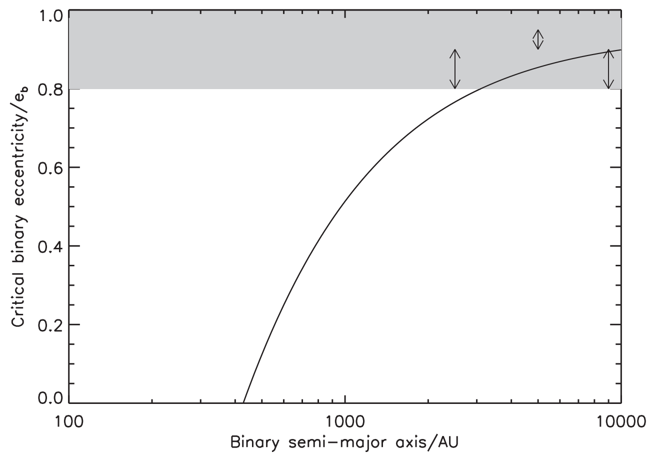

Figure 6. The analytic criterion (solid line) for the stability of circumprimary orbits from Holman & Wiegert (1999, equation 1). The arrows show a comparison with the results of our simulations for the white dwarf phase, on short time-scales. The shaded region indicates the limit of validity of this approximation, $e > 0.8$, which unfortunately corresponds to the region of interest.

the binary removed, in order to remove some dependences on the initial conditions used. For sufficiently high eccentricity companions, it is clear that more material hits the sun than without a binary companion. A conservative approximation to the eccentricity at which this occurs can be obtained from the criterion described in Holman & Wiegert (1999) for the stability of planetary systems orbiting binary systems. Fixing a_{crit} at 60 au in their equation (1), although technically only valid for $e_b < 0.8$, yields approximately the same critical eccentricities for the binary ($e_b > 0.8$; $a_b = 2500$ au; $e_b > 0.9$, $a_b = 5000$ au; $e_b > 0.95$, $a_b = 9000$ au) as found from our simulations (see Fig. 6). Alternative criteria exist for the stability of three body systems (Eggleton & Kiseleva 1995; Petrovich 2015), and although valid for higher eccentricity, have not been derived for two planets orbiting one star, rather than a binary companion and a planet orbiting the central star.

The critical point to take from these simulations is that planetesimals are scattered on to star-grazing orbits whilst a binary companion has high eccentricity, but remain on *more stable* orbits whilst the binary's eccentricity is lower. Thus, planetesimals may survive the star's main-sequence evolution, as well as some proportion of its white dwarf evolution on stable orbits, before being scattered on to star-grazing orbits as the binary's orbit evolves to high eccentricity.

3.4 Caveats and assumptions

The purpose of the above simulations is to illustrate that a wide binary companion could lead to white dwarf pollution at late times by scattering planetesimals on to star-grazing orbits. This requires that sufficient material survives to the white dwarf phase, as well sufficient material is scattered on to star-grazing orbits to produce detectable pollution.

We assume here that planetesimals scattered on to star-grazing orbits lead to white dwarf pollution. This is a fairly robust assumption, as discussed in previous work, although gaps still exist in our knowledge of the exact processes involved (e.g. Jura 2003; Bonsor et al. 2011; Debes et al. 2012; Frewen & Hansen 2014). Planetesimals scattered close to the star are tidally disrupted, and accrete on to the star (Veras et al. 2014b, 2015c), potentially via dusty or gaseous accretion discs (Bochkarev & Rafikov 2011; Hartmann et al. 2011;

Rafikov 2011a,b; Metzger, Rafikov & Bochkarev 2012; Rafikov & Garmilla 2012). Our simulations are good at showing that material is scattered on to star-grazing orbits, but only indicate increased rates of scattering, rather than exact levels, and cannot, therefore, be used to predict accretion rates. However, the amount of material required to produce even the most polluted systems (e.g. a Ceres mass $\sim 10^{-4} M_{\oplus}$ for Dufour et al. 2010 or see fig. 9 of Girven et al. 2012) is low, and our simulations indicate high levels of scattering (Fig. 5). These masses are low compared to typical planetesimal belt masses thought to exist on the main sequence, even those below detection limits (Wyatt et al. 2007; Wyatt 2008), such as the Kuiper belt with its mass of around $0.1\,M_{\oplus}$ (Gladman et al. 2001). Although these masses may be reduced by collisions, or dynamics as material is scattered during the star's main-sequence lifetime, we do not anticipate that in most systems these processes remove sufficient material to prevent detectable pollution being produced (Bonsor & Wyatt 2010), although of course in some planetary systems dynamical clearing may be highly efficient (e.g. Raymond, Armitage & Gorelick 2009, 2010).

We choose to only simulate binaries with fixed eccentricity, in order to simplify our results and save computational time. From this choice, we can clearly show an increased rate of scattering relative to simulations where the binary is not present. However, we miss any changes due to the exact evolution of the system as the binary's orbit increases smoothly in eccentricity, or due to particularities of the exact configuration of the system (e.g. planetesimals with excited eccentricities or inclinations or trapped in resonance, etc.). These details may change the scattering rates. However, given our vague knowledge of the structure of any planetary system, we consider that the present simulations are sufficient to show that material is scattered and a white dwarf could be polluted in this manner.

4 ESTIMATING THE FREQUENCY OF POLLUTION CAUSED BY A WIDE BINARY COMPANION

Having shown that for particular orbital parameters of the binary and planetary system, pollution of the white dwarf can occur, it would be useful to estimate the contribution of this mechanism to the population of polluted white dwarfs. This value first depends on the binary having an appropriate orbit that remains at low eccentricity for the primary's main-sequence evolution, but increases to sufficiently high eccentricity to perturb the primary's planetary system during the primary's white dwarf evolution, and secondly, on the primary having a planetary system with sufficient material that can be scattered on to star-grazing orbits in order to produce the pollution.

4.1 The binary orbit

First, we note that the binary orbits that are most likely to be interesting in terms of the proposed scenario are those at intermediate wide orbits (i.e. $3000 \lesssim a_{\rm b} \lesssim 10\,000$ au). Here, the influence of Galactic tides is strong, but not sufficiently strong that the main-sequence planetary system would have been perturbed (as might occur for larger semimajor axes) and the binary does not orbit too close to the primary, so that the primary's planetary system is only perturbed when the binary's orbit increases significantly in eccentricity.

Here, we estimate the fraction, $f_{\rm WB}$, of wide binaries where the eccentricity of the binary's orbit increases sufficiently (above a critical value), during the white dwarf phase, such that the primary's

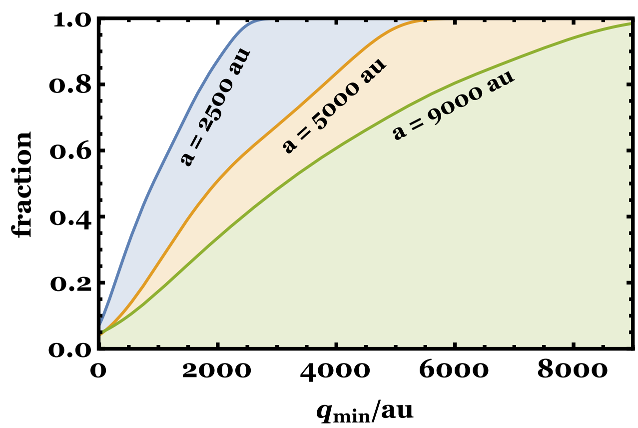

Figure 7. Estimating the fraction of systems where the wide binary mechanism has the potential to pollute the primary's planetary system. Plotted is the cumulative fraction of systems that have a pericentre passage closer than a critical value during the white dwarf phase. The maximum eccentricity (minimum pericentre) can be estimated from Fig. 5; see discussion in Section 4.1 for details.

planetary system is perturbed. The distribution of orbital parameters of wide binaries in the galaxy are not well known. We, therefore, consider a uniform distribution of initial binary eccentricity, e_0, longitude of pericentre, ω_0, sine of inclination to the Galactic plane, $\sin i_0$, and use a Monte Carlo model to select 300 binary orbits for each semimajor axis.[2] We fix the binary semimajor axis at $a_{\rm b} = 9000$ au, $a_{\rm b} = 2500$ au or $a_{\rm b} = 5000$ au and the masses of the pair fixed at $M_{\rm WD} = 0.52\,M_{\odot}$ (evolved from $m_1 = 1\,M_{\odot}$) and $M_2 = 0.8\,M_{\odot}$), in line with Figs 1 and 5. Fig. 7 shows the fraction of systems where a pericentre passage closer than a critical value (or equivalently, the eccentricity evolves to above a critical value), at any point during the white dwarf phase. A maximum time period of 14 Gyr, the age of the Universe, is considered. From Fig. 5, an eccentricity of greater than approximately 0.8 ($a_{\rm b} = 2500$ au), 0.9 ($a_{\rm b} = 5000$ au) or 0.95 ($a_{\rm b} = 9000$ au) is required to perturb a planetary system at 60–100 au. In other words, the binary must enter the region interior to ∼500 au to perturb the planetary system. Fig. 7 shows that 35, 17, and 10 per cent of systems evolve to this pericentre. Although clearly this value will vary significantly with the binary's semimajor axis, we consider 20 per cent to be a reasonable estimate for the fraction of wide binaries with orbital parameters in the correct range to produce polluted white dwarfs.

Another constraint on the orbit of the binary results from the requirement that a planetary system survives, relatively unperturbed, orbiting the primary until late times. This requirement means that the binary's eccentricity must remain below a critical value during the primary's main-sequence evolution. This value can be roughly estimated by considering the criterion of (Holman & Wiegert 1999, equation 1) for stable circumprimary orbits. For example, for our three example binaries with $a_{\rm b} = 2500$, 5000, and 9000 au, the binary eccentricity must remain below $e_{\rm b} < 0.4$, 0.67, and 0.8 (assuming $a_{\rm b} \sim 800$, 1600, and 3000 au on the main sequence), which is not a very strict constraint given the reduced perturbations due to the Galactic tide whilst the primary is on the main sequence and the binary orbit tighter. Given the other uncertainties in our

[2] Tests found no significant difference between using $N = 100$ and 300, so $N = 300$ is assumed to be sufficient.

estimation of the fraction of white dwarfs polluted by the wide binary mechanism, we leave this constraint out of our estimation.

4.2 The planetary system

If $f_{\rm WB} \sim 20$ per cent of wide binaries have orbital parameters such that a close approach occurs during the primary's white dwarf evolution, the next question regards what fraction, $f_{\rm PS}$, of these white dwarfs have planetary systems that can be scattered in such a manner as to produce white dwarf pollution. Our simulations (Section 3) necessarily consider a very specific architecture for the planetary system. Scattering, however, would occur in a wide range of planetary system architectures, including Oort cloud-like structures, rather than Kuiper-like belts. Clearly, the architecture of the planetary system has a great influence on the efficiency at which material is scattered inwards (e.g. Bonsor, Augereau & Thébault 2012), however, for the purposes of this estimation we consider it sufficient to assume that all planetary systems where sufficient material survives have the potential to produce white dwarf pollution via the wide binary mechanism. An advantage of this mechanism is its lack of dependence on the exact structure of the planetary system. Outer planetary systems should survive the star's evolution to the white dwarf phase, although planetesimal belts may become collisionally depleted (Bonsor & Wyatt 2010), and dynamical instabilities may clear some systems of material (e.g. Raymond et al. 2009). Given the prevalence of planetary systems in the Solar neighbourhood (e.g. Borucki et al. 2011; Mullally et al. 2015) and that most planets or planetesimal belts cannot be detected, we consider a reasonable estimate to the fraction of wide binaries, where the white dwarf primary has a planetary system suitable for producing pollution to be $f_{\rm PS} \sim 50$ per cent. We note that this estimate is vague, and is actually something that observations of polluted white dwarfs may help to better constrain.

4.3 Conclusion

We can estimate the fraction of white dwarfs with wide binary companions likely to be polluted by this mechanism, at some point during their lives as white dwarfs, as

$$f_{\rm poll} \sim f_{\rm WB} \times f_{\rm PS} \sim 20\,\text{per cent} \times 50\,\text{per cent} \sim 10\,\text{per cent} \qquad (5)$$

with large uncertainties on our estimations of all of the parameters. At any given instance in time pollution would be detectable in only a fraction, $f_{\rm T}$, of these systems. This fraction will depend on the time-scale on which pollution is detectable following a close approach of the binary star. Many factors, of which are understanding is limited, need to be considered to produce a good estimate for this time-scale, including the dynamical time-scales in the planetary system, lifetime of any accretion disc formed, sinking time-scale of metal pollutants, etc. We anticipate that the dynamical time-scales in the planetary system will dominate, being several orders of magnitude longer than the other time-scales involved here. The dynamical time-scales on which the outer planetary system continues to feed the white dwarf pollution may vary significantly depending on the exact architecture of individual planetary systems. Rather than attempt to approximate these, we, therefore, conclude that a maximum of a few per cent of any sample of white dwarfs with wide binary companions would be observed to have metal pollution produced via the wide binary mechanism presented in this work. The wide binary fraction of white dwarfs is not well known, but if we consider that at least (and probably more than) 10 per cent of white dwarfs should have wide binary companions, based on the 10 per cent of solar-type stars observed with wide binaries (Lépine & Bongiorno 2007; Raghavan et al. 2010, see discussion in the Introduction of this paper), then the wide binary pollution mechanism contributes to pollution in a maximum of a per cent of any sample of white dwarfs.

5 OBSERVATIONAL TESTS

The mechanism presented here works only for a subset of the potential orbital parameters of the binary and planetary system. As discussed in Section 4, this fraction is likely to be of the order of a few per cent of any random sample of white dwarfs with wide binary companions. Given that many observations find that more than 25 per cent, and maybe up to 50 per cent, of white dwarfs are polluted (Zuckerman et al. 2003, 2010; Koester et al. 2014), this wide binary mechanism is only ever going to make a minor contribution, and other mechanisms must be important in polluting white dwarfs. In fact, of roughly one hundred 'pre-Sloan' polluted white dwarfs, discovered by their proper motions, such that any companions is likely to have been found, only five have known common proper motion companions (Farihi et al, private communication). It is not clear whether this wide binary fraction is different from the general population, where, for example ∼10 per cent of solar-type stars are found to have wide separation (>1000 au) companions (Lépine & Bongiorno 2007; Raghavan et al. 2010).

Zuckerman (2014) consider a sample of 17 white dwarfs with wide (>2500 au) companions, all observed with Keck/VLT to search for Ca II, and find that 5/17 (30 per cent) are polluted. With such small number statistics, and significant bias in sample selection, it is difficult to make a good comparison with observations of apparently single white dwarfs, where, for example 25 per cent of DA white dwarfs exhibit Ca pollution (Zuckerman et al. 2003). It remains plausible that the wide binary mechanism could contribute to the pollution in these white dwarfs on the per cent level, but without larger, well defined, samples, it is impossible to make a detailed comparison.

The key evidence for a time-independent mechanism for pollution, such as suggested here, comes from the lack of any decrease in the fraction of polluted systems with age, and the observations of pollution in old (Gyr) white dwarfs, which, for example dynamical instabilities following stellar mass-loss struggle to explain (e.g. Bonsor et al. 2011; Debes et al. 2012; Frewen & Hansen 2014). There are currently insufficient white dwarfs with known binary companions to assess any dependence in the fraction of polluted systems with white dwarf cooling age. However, WD 1009-184, with its companion at 6870 au and an effective temperature of 9940 K (equivalent to a cooling age of ∼700 Myr; Sion et al. 2009; Zuckerman 2014) stands out as a candidate example of where the companion could potentially be responsible for the white dwarf pollution. Future observational searches for companions to cool white dwarfs will provide critical evidence regarding the contribution of wide binaries to pollution. *Gaia* will play a crucial role in discovering companions to many nearby white dwarfs.

6 DISCUSSION

In this work we outline a proof of concept that illustrates the manner by which a wide binary companion could lead to pollution in white dwarfs. In Section 2, we illustrate that during the evolution of the binary's orbit as it interacts with the Galactic tides, periods of increased eccentricity occur. These periods are most likely to occur during the white dwarf phase, due to the increase in separation of the binary orbit following stellar mass-loss. We claim that a wide binary companion whose eccentricity increases for the first time during the primary star's white dwarf evolution has the potential to perturb any planetary system orbiting the white dwarf. In Section 3, we illustrated how planetesimals can be scattered on to star-grazing orbits, a pre-requisite for pollution of the white dwarf's atmosphere. This mechanism is independent of white dwarf cooling age, and could, therefore, produce pollution around old (1–5Gyr) white dwarfs that other mechanisms struggle to explain. We estimate that this mechanism may contribute to the total fraction of polluted white dwarfs on the level of a few per cent. There are no current observational samples that are sufficiently large to assess whether the population of polluted white dwarfs around single stars is different to those with companions.

We consider that this mechanism is robust and will occur for white dwarfs with planetary systems and companions with the 'correct' parameters. The weakest part of this argument regards the link between planetesimals scattered inwards and the pollution of white dwarf atmospheres, which was not investigated in this work. The tidal disruption of planetesimals and the accretion of close-in dusty material on to white dwarfs have been previously investigated (e.g. Rafikov 2011a,b; Debes et al. 2012; Metzger et al. 2012; Veras et al. 2014b, 2015c), although some gaps still remain in our understanding. Our discussion of whether a detectable level of pollution is produced is vague (see Section 4), and it remains possible that no detectable pollution is ever produced by planetesimal scattering. However, our simulations do show a significant increase in the number of planetesimals scattered on to star-grazing orbits with a binary companion on an eccentric orbit, compared to without a binary companion (see Fig. 5), and given the low accretion masses required to produce detectable pollution,[3] it remains plausible that the mechanism presented works for some region of the parameter space. In fact, we anticipate that this mechanism has a weak dependence on the exact architecture of the planetary system, and a much stronger dependence on the orbital parameters of the binary.

The purpose of this work was to outline a potential mechanism for the pollution of white dwarfs. We do not consider our estimation of the fraction of white dwarfs with wide binary companions polluted by this mechanism to be robust, and it is even trickier to determine the fraction of an observational sample that would be caught whilst displaying detectable pollution. Our estimation does, however, indicate that the wide binary mechanism is not the dominant mechanism for producing white dwarf pollution, even at late times, and that statistics in current observational samples are insufficient to determine whether or not this mechanism is producing pollution. *Gaia* and future observational searches for companions to nearby white dwarfs, should enable a clearer determination of its contribution.

We have ignored the potential for exchange interactions, or changes to the binary's orbit, which could have a big effect on the evolution of individual systems, but are not going to significantly affect the total population of white dwarfs with wide binary companions. We have also ignored any potential evolution of the companion star. If it loses a significant fraction of its mass, this could increase the fraction of binary orbits that meet our criteria for producing pollution, as in essence the system has double the chance of entering the correct regime. For example, one could imagine that the expansion in the orbit of the binary is insufficient to induce large perturbations from the Galactic tide as the primary loses mass to become a white dwarf, but becomes sufficiently wide once the secondary evolves to become a white dwarf. Perturbations could occur to planetary systems orbiting either the primary or the secondary.

Our mechanism depends critically on the survival of a planetary system, containing sufficient material, to late times in the white dwarf phase. Although, theoretically there are good arguments for the survival of outer planetary systems during post-main sequence evolution (Duncan & Lissauer 1998; Veras & Wyatt 2012), even if collisionally depleted (Bonsor & Wyatt 2010), there is a yet little direct observational evidence for the presence of planetary systems around white dwarfs (Burleigh et al. 2008; Mullally et al. 2008; Xu et al. 2015), although a few potential exceptions exist (Luhman, Burgasser & Bochanski 2011; Marsh et al. 2014). Planets have been detected around giant stars (e.g. Johnson et al. 2007, 2008; Sato et al. 2008) and horizontal branch stars (Silvotti et al. 2007). Dusty, debris-like discs have been observed at the centre of several planetary nebulae (Su et al. 2007; Chu et al. 2011), very early in the white dwarf phase. If future observations show that this mechanism is a significant contributor to white dwarf pollution, it provides further evidence for the survival of outer planetary systems to the white dwarf phase.

The most important contribution of the wide binary mechanism presented here is to the pollution of old (Gyr) white dwarfs, that are hard to explain by other mechanisms. The mechanism is independent of white dwarf cooling age, except for any variation in the planetary system itself. On the main-sequence material can be depleted, both by collisions and dynamics, with a steep time dependence. By the white dwarf phase, collisional time-scales are long (Bonsor & Wyatt 2010), and the system is much more likely to have reached a dynamically stable state, such that any such evolution is likely to only occur at low levels.

7 CONCLUSIONS

In this work, we present a mechanism to explain the metal pollution observed in many white dwarfs, especially at late times. The orbits of wide binaries vary periodically with the Galactic tides. The influence of the Galactic tide increases following stellar mass-loss. Thus, a wide binary may evolve for Gyr at large separations, and yet, have a close approach for the *first time* during the primary's white dwarf phase. Such a close approach could perturb any planetary system orbiting the primary, potentially scattering planetesimals on to star-grazing orbits.

We present simulations that illustrate the change in orbital parameters of the binary (Section 2) and the scattering of planetesimals on to star-grazing orbits (Section 3). These demonstrations should be considered a proof of concept, rather than a detailed analysis. We estimate that this mechanism could contribute to pollution in up to a few per cent of any sample of white dwarfs with wide binary companions, and up to a per cent of all white dwarfs (Section 4), independent of the age of the white dwarf. Current observational samples do not have sufficient statistics to indicate whether or not this mechanism provides an important contribution to pollution in white dwarfs. The calcium-polluted, WD 1009-184, with its companion at 6870 au and an effective temperature of 9940 K (equivalent to a cooling age of ∼700 Myr; Sion et al. 2009; Zuckerman 2014) stands out as an example system where this mechanism could be acting.

Wide binary pollution is unlikely to be the sole contributor to the population of metal-polluted white dwarfs. Instead, we envisage

[3] Even one of the most highly polluted white dwarfs only needs a Ceres mass (10^{-4} $M_\oplus$) (Dufour et al. 2010), or see Girven et al. (2012).

that it acts alongside other mechanisms, adding a time-independent pollution rate. Future observational searches for wide binary companions to nearby white dwarfs (e.g. with *Gaia*) and an increased sample of metal-enriched old, white dwarfs are required to determine whether or not wide binary companions play an important role in white dwarf pollution.

ACKNOWLEDGEMENTS

We thank Silvia Catalán and Jay Farihi for useful discussions. We thank the referee Dr Cristobal Petrovich for his useful comments that improved the quality of the manuscript. AB was supported by ANR-2010 BLAN-0505- 01(EXOZODI), NERC Grant NE/K004778/1, and ERC grant number 279973 whilst conducting this research. DV benefitted from support by the European Union through ERC Grant Number 320964.

REFERENCES

Aannestad P. A., Kenyon S. J., Hammond G. L., Sion E. M., 1993, AJ, 105, 1033
Adams F. C., Bloch A. M., 2013, ApJ, 777, L30
Alcock C., Fristrom C. C., Siegelman R., 1986, ApJ, 302, 462
Barstow M. A., Barstow J. K., Casewell S. L., Holberg J. B., Hubeny I., 2014, MNRAS, 440, 1607
Bear E., Soker N., 2013, New Astron., 19, 56
Bochkarev K. V., Rafikov R. R., 2011, ApJ, 741, 36
Bonsor A., Wyatt M., 2010, MNRAS, 409, 1631
Bonsor A., Wyatt M. C., 2012, MNRAS, 420, 2990
Bonsor A., Mustill A. J., Wyatt M. C., 2011, MNRAS, 414, 930
Bonsor A., Augereau J.-C., Thébault P., 2012, A&A, 548, A104
Borucki W. J. et al., 2011, ApJ, 736, 19
Brasser R., 2001, MNRAS, 324, 1109
Breiter S., Ratajczak R., 2005, MNRAS, 364, 1222
Breiter S., Dybczynski P. A., Elipe A., 1996, A&A, 315, 618
Burleigh M. R. et al., 2008, MNRAS, 386, L5
Cassan A. et al., 2012, Nature, 481, 167
Chambers J. E., 1999, MNRAS, 304, 793
Chu Y. et al., 2011, ApJ, 142, 75
Debes J. H., Sigurdsson S., 2002, ApJ, 572, 556
Debes J. H., Walsh K. J., Stark C., 2012, ApJ, 747, 148
Dufour P., Kilic M., Fontaine G., Bergeron P., Lachapelle F., Kleinman S. J., Leggett S. K., 2010, ApJ, 719, 803
Duncan M. J., Lissauer J. J., 1998, Icarus, 134, 303
Eggleton P., Kiseleva L., 1995, ApJ, 455, 640
Eiroa C. et al., 2013, A&A, 555, A11
Farihi J., Becklin E. E., Zuckerman B., 2005, ApJS, 161, 394
Farihi J., Barstow M. A., Redfield S., Dufour P., Hambly N. C., 2010, MNRAS, 404, 2123
Farihi J., Dufour P., Napiwotzki R., Koester D., 2011, MNRAS, 413, 2559
Frewen S. F. N., Hansen B. M. S., 2014, MNRAS, 439, 2442
Gänsicke B. T., Marsh T. R., Southworth J., Rebassa-Mansergas A., 2006, Science, 314, 1908
Gänsicke B. T., Marsh T. R., Southworth J., 2007, MNRAS, 380, L35
Gänsicke B. T., Koester D., Farihi J., Girven J., Parsons S. G., Breedt E., 2012, MNRAS, 424, 333
Girven J., Brinkworth C. S., Farihi J., Gänsicke B. T., Hoard D. W., Marsh T. R., Koester D., 2012, ApJ, 749, 154
Gladman B., Kavelaars J. J., Petit J.-M., Morbidelli A., Holman M. J., Loredo T., 2001, AJ, 122, 1051
Graham J. R., Matthews K., Neugebauer G., Soifer B. T., 1990, ApJ, 357, 216
Hartmann S., Nagel T., Rauch T., Werner K., 2011, A&A, 530, A7
Heisler J., Tremaine S., 1986, Icarus, 65, 13
Holberg J. B., Sion E. M., Oswalt T., McCook G. P., Foran S., Subasavage J. P., 2008, AJ, 135, 1225
Hollands M. A., Gänsicke B. T., Koester D., 2015, MNRAS, 450, 681
Holman M. J., Wiegert P. A., 1999, AJ, 117, 621
Hurley J. R., Pols O. R., Tout C. A., 2000, MNRAS, 315, 543
Johnson J. A. et al., 2007, ApJ, 665, 785
Johnson J. A., Marcy G. W., Fischer D. A., Wright J. T., Reffert S., Kregenow J. M., Williams P. K. G., Peek K. M. G., 2008, ApJ, 675, 784
Jura M., 2003, ApJ, 584, L91
Jura M., 2004, ApJ, 603, 729
Jura M., 2006, ApJ, 653, 613
Jura M., 2008, AJ, 135, 1785
Jura M., Farihi J., Zuckerman B., Becklin E. E., 2007, AJ, 133, 1927
Kaib N. A., Raymond S. N., Duncan M., 2013, Nature, 493, 381
Kilic M., Redfield S., 2007, ApJ, 660, 641
Kilic M., von Hippel T., Leggett S. K., Winget D. E., 2006, ApJ, 646, 474
Klein B., Jura M., Koester D., Zuckerman B., Melis C., 2010, ApJ, 709, 950
Klein B., Jura M., Koester D., Zuckerman B., 2011, ApJ, 741, 64
Koester D., Wilken D., 2006, A&A, 453, 1051
Koester D., Provencal J., Shipman H. L., 1997, A&A, 320, L57
Koester D., Girven J., Gänsicke B. T., Dufour P., 2011, A&A, 530, A114
Koester D., Gänsicke B. T., Farihi J., 2014, A&A, 566, A34
Kouwenhoven M. B. N., Goodwin S. P., Parker R. J., Davies M. B., Malmberg D., Kroupa P., 2010, MNRAS, 404, 1835
Kudritzki R. P., Reimers D., 1978, A&A, 70, 227
Lépine S., Bongiorno B., 2007, AJ, 133, 889
Luhman K. L., Burgasser A. J., Bochanski J. J., 2011, ApJ, 730, L9
Makarov V. V., Zacharias N., Hennessy G. S., 2008, ApJ, 687, 566
Marsh T. R. et al., 2014, MNRAS, 437, 475
Marzari F., Weidenschilling S. J., Barbieri M., Granata V., 2005, ApJ, 618, 502
Matese J. J., Whitman P. G., 1989, Icarus, 82, 389
Matese J. J., Whitman P. G., 1992, Celest. Mech. Dyn. Astron., 54, 13
Matese J. J., Whitman P. G., Innanen K. A., Valtonen M. J., 1995, Icarus, 116, 255
Mayor M. et al., 2011, preprint (arXiv:e-prints)
Melis C., Jura M., Albert L., Klein B., Zuckerman B., 2010, ApJ, 722, 1078
Metzger B. D., Rafikov R. R., Bochkarev K. V., 2012, MNRAS, 423, 505
Mullally F., Winget D. E., De Gennaro S., Jeffery E., Thompson S. E., Chandler D., Kepler S. O., 2008, ApJ, 676, 573
Mullally F. et al., 2015, ApJS, 217, 31
Mustill A. J., Villaver E., 2012, ApJ, 761, 121
Mustill A. J., Veras D., Villaver E., 2014, MNRAS, 437, 1404
Parravano A., McKee C. F., Hollenbach D. J., 2011, ApJ, 726, 27
Petrovich C., 2015, ApJ, 808, 120
Rafikov R. R., 2011a, ApJ, 732, L3
Rafikov R. R., 2011b, MNRAS, L287
Rafikov R. R., Garmilla J. A., 2012, ApJ, 760, 123
Raghavan D. et al., 2010, ApJS, 190, 1
Raymond S. N., Armitage P. J., Gorelick N., 2009, ApJ, 699, L88
Raymond S. N., Armitage P. J., Gorelick N., 2010, ApJ, 711, 772
Sato B. et al., 2008, PASJ, 60, 1317
Silvotti R. et al., 2007, Nature, 449, 189
Sion E. M., Holberg J. B., Oswalt T. D., McCook G. P., Wasatonic R., 2009, AJ, 138, 1681
Stone N., Metzger B. D., Loeb A., 2015, MNRAS, 448, 188
Su K. Y. L. et al., 2007, ApJ, 657, L41
van Maanen A., 1920, Contributions from the Mount Wilson Observatory/ Carnegie Institution of Washington, 182, 1
Vassiliadis E., Wood P. R., 1993, ApJ, 413, 641
Veras D., Evans N. W., 2013a, Celest. Mech. Dyn. Astron., 115, 123
Veras D., Evans N. W., 2013b, MNRAS, 430, 403
Veras D., Gänsicke B. T., 2015, MNRAS, 447, 1049
Veras D., Tout C. A., 2012, MNRAS, 422, 1648
Veras D., Wyatt M. C., 2012, MNRAS, 421, 2969
Veras D., Wyatt M. C., Mustill A. J., Bonsor A., Eldridge J. J., 2011, MNRAS, 417, 2104
Veras D., Hadjidemetriou J. D., Tout C. A., 2013, MNRAS, 435, 2416
Veras D., Mustill A. J., Bonsor A., Wyatt M. C., 2013, MNRAS, 431, 1686
Veras D., Evans N. W., Wyatt M. C., Tout C. A., 2014a, MNRAS, 437, 1127

Veras D., Leinhardt Z. M., Bonsor A., Gänsicke B. T., 2014b, MNRAS, 445, 2244
Veras D., Jacobson S. A., Gänsicke B. T., 2014c, MNRAS, 445, 2794
Veras D., Shannon A., Gänsicke B. T., 2014d, MNRAS, 445, 4175
Veras D., Eggl S., Gaensicke B. T., 2015a, preprint (arXiv:e-prints)
Veras D., Eggl S., Gänsicke B. T., 2015b, MNRAS, 451, 2814
Veras D., Leinhardt Z. M., Eggl S., Gänsicke B. T., 2015c, MNRAS, 451, 3453
Villaver E., Livio M., 2007, ApJ, 661, 1192
Villaver E., Livio M., 2009, ApJ, 705, L81
Villaver E., Livio M., Mustill A. J., Siess L., 2014, ApJ, 794, 3
von Hippel T., Kuchner M. J., Kilic M., Mullally F., Reach W. T., 2007, ApJ, 662, 544
Voyatzis G., Hadjidemetriou J. D., Veras D., Varvoglis H., 2013, MNRAS, 430, 3383
Wyatt M. C., 2008, ARA&A, 46, 339
Wyatt M. C., Smith R., Su K. Y. L., Rieke G. H., Greaves J. S., Beichman C. A., Bryden G., 2007, ApJ, 663, 365
Wyatt M. C., Farihi J., Pringle J. E., Bonsor A., 2014, MNRAS, 439, 3371
Xu S., Ertel S., Wahhaj Z., Milli J., Scicluna P., Bertrang G. H.-M., 2015, preprint (arXiv:e-prints)
Zuckerman B., 2014, ApJ, 791, L27
Zuckerman B., Koester D., Reid I. N., Hünsch M., 2003, ApJ, 596, 477
Zuckerman B., Melis C., Klein B., Koester D., Jura M., 2010, ApJ, 722, 725

This paper has been typeset from a TEX/LATEX file prepared by the author.