Planetary Systems Around White Dwarfs

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ABSTRACT

White dwarf planetary science is a rapidly growing field of research featuring a diverse set of observations and theoretical explorations. Giant planets, minor planets, and debris discs have all been detected orbiting white dwarfs. The innards of broken-up minor planets are measured on an element-by-element basis, providing a unique probe of exoplanetary chemistry. Numerical simulations and analytical investigations trace the violent physical and dynamical history of these systems from au-scale distances to the immediate vicinity of the white dwarf, where minor planets are broken down into dust and gas and are accreted onto the white dwarf photosphere. Current and upcoming ground-based and space-based instruments are likely to further accelerate the pace of discoveries.

Subject headings: Asteroids, Planets, White Dwarfs, Discs, Geochemistry, Planetary Interiors, Planet Formation, Celestial Mechanics, Tides, Evolved Stars

1. Introduction

White dwarf exoplanetary systems provide windows into composition, physical processes and minor planets (asteroids, comets, moons, and interior fragments of larger planets) which are unavailable in main-sequence investigations. Almost every known exoplanet orbits a star that will become a white dwarf, and these exoplanets will either survive or be destroyed throughout the stellar transformation. En route, the exoplanets’ perturbations on smaller bodies contribute to the latter’s physical and dynamical evolution, allowing them to approach and be destroyed by the white dwarf. The resulting remnants are ubiquitously observable, such that the occurrence rate of white dwarf planetary systems is comparable to that of main-sequence exoplanetary systems.

In fact, planetary systems around white dwarfs have now been observed at a variety of stages of destruction, from fully intact planets to those which have been shredded down...
to their constituent chemical elements. Theoretical models need to explain an expanding variety of planetary system signatures, which include intact solid bodies, partially disrupting solid bodies, remnant discs and rings, dry, wet and differentiated chemical signatures, and accretion onto and diffusion within white dwarf photospheres. These observational signatures have been acquired from a striking diversity of discovery techniques and instruments, and new findings continue to surprise and delight.

This article is focussed on the demographics of and theoretical explanations for white dwarf planetary systems, and does not highlight planetary system investigations which emphasize the effects of giant branch stars (the immediate precursors to white dwarf stars). For a pre-2016 review of giant branch planetary systems, see Veras (2016a).

2. Demographics

Signatures of white dwarf planetary systems can be split into four categories: (i) major planets (with radii $\gtrsim 10^3$ km), (ii) minor planets (with radii $\lesssim 10^3$ km), (iii) discs and rings, and (iv) photospheric metal chemistry (often characterized as “pollution”).

The raw numbers and occurrence rates of each of these four categories are dependent on one’s confidence level about a particular observation or set of observations. An ongoing controversy in main-sequence exoplanetary science is whether to classify a potential planetary object as “validated”, “confirmed” or as a “candidate” or “brown dwarf”. In white dwarf planetary science, these terms are even less well-defined, particularly for the major and minor planets, partly because some spectroscopic discovery methods are new (whereas transit photometry and imaging are used similarly in both main-sequence and white dwarf communities). Given this caveat, this article will not use any of these quoted adjectives; readers can decide for themselves which are most appropriate through a careful analysis of the discovery papers.

In terms of raw numbers of white dwarf planetary systems, as of the beginning of 2021, this article assumes the discovery of 4 major planets, at least 3 minor planets, over 60 discs or rings, and over 1,000 white dwarfs with photospheric planetary debris (Figs. 1-4). In terms of occurrence rates, about one-quarter to one-half of Solar neighbourhood white dwarfs feature photospheric metal chemistry. Discs are assumed to orbit nearly all these chemically enriched white dwarfs, and none of the un-enriched white dwarfs. Predicted occurrence rates of major and minor planets suffer from significant observational biases, and theoretical models could only fill in these gaps with multiple assumptions in the high degree-of-freedom parameter space (Fig. 6).
Fig. 1.— Four major planets orbiting white dwarfs. Planet type is shown in green boxes, and the primary discovery method in blue boxes. The separations given are sky-projected, rather than actual.
2.1. Major planets

The four major planets which orbit white dwarfs (Thorsett, Arzoumanian & Taylor 1993; Sigurdsson et al. 2003; Luhman, Burgasser & Bochanski 2011; Gänzicke et al. 2019; Vanderburg et al. 2020) are illustrated with cartoons in Fig. 1. Although the sizes of these systems are not to scale, the placement of all four on the same figure highlights their diversity in terms of primary discovery method (imaging, spectroscopy, photometry, pulsar timing, astrometry) and architecture (circumbinary with a pulsar and white dwarf for the PSR B1620-26AB system, and circumstellar with a white dwarf for the other three, including two M-star companions in the WD 1856+534 system). The planet-white dwarf separations range from 0.02 au to about 2,500 au, with a notable absence of planets in the few au range due to observational bias.

Significantly, all four planets are giant planets; so far, no known terrestrial-sized exoplanets around white dwarfs have been discovered, again likely due to observational bias. The mass of PSR B1620-26AB b is about $2.5 \pm 1.0 M_{\text{Jup}}$ (Sigurdsson et al. 2003) and the mass of WD 0806-661 b is about $7 \pm 1 M_{\text{Jup}}$ (Luhman, Burgasser & Bochanski 2011). The masses of the other two planets are not as well constrained: for WD J0914+1914 b, observations do not provide limits except for requiring that the planet is consistent with the mass of an ice giant (Gänzicke et al. 2019). Theoretical constraints, however, suggest that the planet is inflated and underdense (Veras & Fuller 2020), which would restrict the potential ice giant mass range. The mass of WD 1856+534 b has an upper limit of $14 M_{\text{Jup}}$ (Vanderburg et al. 2020), and a lower limit of about $2 M_{\text{Jup}}$ (Alonso et al. 2021).

The probable origins of all four major planets are strikingly different. Because PSR B1620-26AB b is a cluster planet which orbits both a pulsar and a white dwarf, the dynamical history of the system likely includes a triple interaction within the cluster, potentially involving a common envelope (Beer, King & Pringle 2004; Sigurdsson & Thorsett 2005). The wide separation of WD 0806-661 b ensures that it did not form in-situ (Rodriguez et al. 2011). Instead, the planet’s current location my be explained by a previous gravitational scattering event within the system, or from a dissipative capture from an external companion or cluster. In contrast, the close separations of WD J0914+1914 b and WD 1856+534 b require either (i) a gravitational scattering event during the white dwarf phase, plus some form of tidal shrinkage (Muñoz & Petrovich 2020; O’Connor, Liu & Lai 2021; Veras & Fuller 2020; Veras 2020; Zotos et al. 2020; Stephan, Naoz & Gaudi 2021), or (ii) survival of the planet within a common envelope of the white dwarf precursor (Chamandy et al. 2021; Lagos et al. 2021).

2.2. Minor planets

Despite the crucial role of major planets as agents of debris delivery, they have been found in $< 1\%$ of currently known white dwarf planetary systems (Dufour et al. 2007; Kleinman et al. 2013; Kepler et al. 2015, 2016; Coutu et al. 2019). All other observations of
Fig. 2.— Known and probable minor planets orbiting white dwarfs, at various early stages of disruption. The green boxes feature minor planet type, and the blue boxes feature primary discovery technique. The lower-right plot is © AAS. Reproduced with permission.
signatures in these systems are thought to arise directly from minor planets. This subsection, which is based on Fig. 2, summarizes the known minor planets which are intact or are in the early stages of disruption; subsections 2.3-2.4 detail the more evolved stages of minor planet debris.

Transit photometry has so far been responsible for all minor planet discoveries (Vanderburg et al. 2015; Vanderbosch et al. 2020; Guidry et al. 2021) except in the SDSS J1228+1040 system (Manser et al. 2019). Unlike the transit curves which are usually seen in main-sequence exoplanetary science, the transit curves for the minor planets orbiting WD 1145+017 and ZTF J0139+5245 (and possibly systems like SDSS J0107+2107, ZTF J0328-1219, and SBSS 1232+563) (i) are not of solid bodies but rather predominantly dusty effluences, (ii) contain trackable features which can change on weekly, monthly and yearly timescales, and (iii) can have maximum transit depths exceeding 50%. These minor planets are hence not intact, but are in various stages of ongoing disruption.

The WD 1145+017 system (Vanderburg et al. 2015) has received more attention than any other white dwarf planetary system, with over 20 papers dedicated to follow-up observations; see Vanderburg & Rappaport (2018) for a pre-2018 review. This extensive attention was likely due to a few factors: (i) The system contains the first minor or major planet that was discovered close to a single white dwarf, providing stark affirmation that planets can reach such close orbits and thereby removing any lingering doubts about the origin of the photospheric and disc metals, (ii) the system is easily observed by professionals and amateurs alike due to a 4.5-hour orbital period of transiting debris, and (iii) the system is exciting and fun to observe because of the variable debris features.

Substantial theoretical work on this system (Rappaport et al. 2016; Farihi, von Hippel & Pringle 2017b; Gurri, Veras & Gänsicke 2017; Veras et al. 2017a; Xu et al. 2019a; Duvvuri, Redfield & Veras 2020; O’Connor & Lai 2020) has placed constraints on the progenitor minor planet mass (about 10% of Ceres’ mass), bulk density (Vesta-like), interior structure (probably differentiated), placement relative to the circumstellar dust and gas in the system, and dynamical history through tidal shrinkage and circularization and ram pressure drag. Because the minor planet effluences orbit WD 1145+017 at a near-constant separation of 0.005 au, which corresponds to the rubble-pile disruption (Roche) limit, the disruption in that system is assumed to be tidal.

The origin of the disruption in ZTF J0139+5245 (Vanderbosch et al. 2020) is not as clear. The dusty effluences are on a 0.36 au orbit, which would need to have an eccentricity exceeding about 0.97 in order for tidal disruption to generate the debris; alternatively, rotational fission may occur outside of the Roche radius, allowing for breakup to occur beyond distances of 0.005 au (Veras, McDonald & Makarov 2020a). Transit signatures of other minor planets (Guidry et al. 2021) represent, at this time, robust hints of minor planets rather than definitive detections.

Unlike all of the minor planets detected by transit photometry, the spectroscopically-determined minor planet orbiting SDSS J1228+1040 (Manser et al. 2019) was identified
Fig. 3.— Four highlighted aspects of planetary discs and rings orbiting white dwarfs. The velocity map (upper left) illustrates non-axisymmetric disc geometry. The dust variability plot (upper right) suggests widespread dynamical activity over yearly and decadal timescales, whereas the outburst event (lower left) is sudden. The chemistry plot (lower right) is our best example of dusty disc chemistry. The bottom two plots are © AAS. Reproduced with permission.
through variability in Ca II triplet emission, which provides geometric disc information. This minor planet is embedded within the disc, does not appear to be disrupting, and resides well within the rubble-pile Roche radius, at a distance of about 0.003 au. This combination of features suggests that the body is actually an iron-rich planetary core with tensile strength and internal viscosity (O’Connor & Lai 2020).

2.3. Discs and rings

The products of minor planet break-up have been commonly denoted in the literature as a “disc” and are detected through infrared excesses on spectral energy distributions (for dust) and key emission and absorption spectral signatures (for gas). This disc nomenclature refers to structures contained within about 0.005 au ($R_{\text{Sun}}$) of the white dwarf and ignores (unobservable) debris fields or belts extending beyond about 10 solar radii from the white dwarf. This nomenclature may also erroneously give the impression of an ordered, circular-shaped structure with well-defined inner and outer boundaries. In fact, these structures can be wispy, ring-like, eccentric (Gänside et al. 2006; Dennihy et al. 2016; Manser et al. 2016a; Nixon et al. 2021) and variable (Fig. 3).

The number of detections of these discs and rings now exceed about 60 (Dennihy et al. 2020; Manser et al. 2020; Melis et al. 2020; Xu, Lai & Dennihy 2020; Gentile Fusillo et al. 2021) and their discoveries extend back to Zuckerman & Becklin (1987); for a pre-2016 review, see Farihi (2016), and for a more recent review in comparison to main-sequence debris discs, see Chen, Su & Xu (2020). All of these discs are circumstellar except for one circumbinary exception (Farihi, Parsons & Gänside 2017a).

Nearly all of the discs contain dust; a notable exception being the all-gas disc around WD J0914+1914, which also hosts a major planet (Fig. 1). About 1-3% of all white dwarfs contain observable dusty discs (Farihi, Jura & Zuckerman 2009) and about 4% of dusty discs contain observable gas (Manser et al. 2020); a couple of notable discs which contain both observable gas and dust are WD J145+017 and SDSS J1228+1040, which also host minor planets (Fig. 2). The true fraction of white dwarfs with discs is likely much higher (Rocchetto et al. 2015; Bonsor et al. 2017), and probably is similar to the fraction of white dwarfs containing photospheric metal debris (25-50%). White dwarf discs do not appear to be more numerous in systems with binary main-sequence stellar companions (Wilson et al. 2019).

One of the most exciting aspects of these discs is that they showcase activity beyond standard Keplerian motion around the white dwarf. One manifestation of the activity is through flux changes due to some physical process in the dust (Xu & Jura 2014; Farihi et al. 2018a; Xu et al. 2018; Wang et al. 2019; Rogers et al. 2020; Swan et al. 2020; Wilson, Hermes & Gänside 2020). Another manifestation is through the secular (long-term) precession of gas, as well as its variability (Wilson et al. 2014; Manser et al. 2016a; 2019, 2021; Redfield et al. 2017; Cauley et al. 2018; Dennihy et al. 2018, 2020; Fortin-Archambault, Dufour & Xu
Fig. 4.— Four examples of exoplanetary chemistry from debris in white dwarf photospheres, commonly referred to as white dwarf pollution. The majority of pollutants are dry and Earth-like (upper left) despite notable water-rich exceptions (upper right). Differentiated progenitors of the pollutants (lower left) may be traced back to formation locations in the protoplanetary birth disc (lower right). The upper left plot is © AAS. Reproduced with permission.
Fig. 5.— All planetary metals (chemical elements heavier than helium) found in white dwarf photospheres, partitioned by the geochemical Goldschmidt classification. Hydrogen is also accreted and can sometimes be measured. The table of discoveries is taken from the first three columns of Table 1 of [Klein et al. (2021)]; for notes, references and additional details, see that paper.
Both dust and gas can also represent windows into composition, although planetary chemistry is primarily obtained from photospheric debris measurements (subsection 2.4). Pre-JWST, the only dusty disc close enough and bright enough to Earth for which chemical constraints can be modelled in detail orbits G 29-38 (Reach et al. 2005, 2009); broader chemical dust models can still be fit around other white dwarfs (Xu et al. 2018). Circumstellar gas offers greater opportunities (Melis et al. 2010; Hartmann et al. 2011, 2014; Xu et al. 2016) and crucially allows one to match the chemistry in the disc with the chemistry in the photosphere (Gänsicke et al. 2019; Steele et al. 2021).

### 2.4. Photospheric chemistry

After being ground down and converted into gas, the planetary debris is finally accreted onto the photosphere of the white dwarf. Particularly strong objects such as SDSS J1228+1040 b may also impact the white dwarf photosphere directly when dynamically perturbed. The high density of the white dwarf then stratifies the accreted debris into its constituent chemical elements. These so-called “metals” are detectable because they stand out against a backdrop of primarily hydrogen and helium, giving rise to the common term “pollution”. Uniform samples of single white dwarfs with similar properties have revealed that 25-50% of all single white dwarfs are polluted (Zuckerman et al. 2003, 2010; Koester, Gänsicke & Farihi 2014), with the total number standing at over 1,000 (Coutu et al. 2019). For white dwarfs in binaries (Zuckerman 2014; Bonsor et al. 2021), winds from main-sequence stellar companions negligibly contribute to photospheric pollution unless the binary orbit is smaller than a few au (Debes 2006; Veras, Xu & Rebassa-Mansergas 2018).

The accreted matter directly probes exoplanetary chemistry, and at a high level of detail (Figs. 4-5). The pioneering study of Zuckerman et al. (2007) demonstrated how abundances of over a dozen metals in a single white dwarf can be pieced together to infer the chemical composition of the progenitor minor planet. Since then, a multitude of abundance studies have focussed on interesting individual white dwarfs or ensembles of white dwarfs; see Jura & Young (2014) for a pre-2014 review. Usually, these studies (e.g. Klein et al. 2010; Gänsicke et al. 2012; Xu et al. 2013; Barstow et al. 2014; Jura et al. 2014; Xu et al. 2014; Jura et al. 2015; Wilson et al. 2015; Farihi et al. 2016; Melis & Dufour 2017; Xu et al. 2019b) analyze white dwarfs with at least three different metals; the majority of polluted white dwarfs have only one or two (typically calcium and magnesium) which exceed the detection threshold.

The high quality of the data and modelling now allows for detailed comparisons to the compositions of a variety of solar system meteorites and planets (Blouin et al. 2019; Swan et al. 2019; Doyle et al. 2019, 2020), including investigations of the carbon-to-oxygen ratio (Wilson et al. 2016), the level of differentiation in and mixing amongst the progenitor minor planets (Jura, Xu & Young 2013; Hollands, Gänsicke & Koester 2018; Bonsor et al. 2020; Turner & Wyatt 2020), and the formation locations and level of post-nebula de-volatilization
of the progenitors (Harrison, Bonsor & Madhusudhan 2018; Harrison, Shorttle & Bonsor 2021). Although the vast majority of pollutants are “dry” (volatile-poor) and Earth-like in composition, exciting exceptions include white dwarfs with water-rich progenitors (Farhi, Gänsicke & Koester 2013; Raddi et al. 2015; Gentile Fusillo et al. 2017; Hoskin et al. 2020; Izquierdo et al. 2021), a Kuiper belt-like comet/asteroid (Xu et al. 2017) and an exomoon (Doyle, Desch & Young 2021). Over 20 metals in total have now been found (Fig. 5), with the last four being nitrogen (Xu et al. 2017), lithium and potassium (Hollands et al. 2021; Kaiser et al. 2021), and beryllium (Klein et al. 2021).

3. Explanations

By itself, the drive to understand the fate of planetary systems has prompted innovative theoretical investigations. Additional motivation arises from the plethora of increasingly diverse observations of white dwarf planetary systems that were summarized in Section 2. These theoretical investigations can be split into two categories, which are the subject of subsections 3.1 and 3.2: (i) planetary architectures and (ii) activity close to and inside of the white dwarf. A comprehensive accounting of theoretical investigations pre-2016 can be found in Veras (2016a).

3.1. Planetary architectures

All planetary signatures in single white dwarf systems are the end result of gravitational and radiative perturbations amongst major and minor planets at distances well beyond several solar radii, usually beyond observable limits. Because these perturbations are linked with the evolution of the central star, investigations often evolve both the star and planetary system simultaneously.

The parameter space to explore is large: at minimum, 6 orbital elements and a mass must be provided for each major and minor planet. Further, observations of these planets are not yet numerous enough to constrain this parameter space. Consequently, investigators have largely relied on a “divide and conquer” approach in the literature, restricting individual investigations to a specific family of architectures. These families are broadly categorized in Figure 6 in terms of number of stars, number of major planets, and whether minor planets were included in each investigation.

Amongst minor planets, different types have been modelled: (i) most commonly, asteroids in analogues of the main belt, Kuiper belt and scattered disc, (ii) comets in Oort cloud analogues (Alcock, Fristom & Siegelman 1986; Parriott & Alcock 1998; Veras, Shannon & Gänsicke 2014a; Stone, Metzger & Loeb 2015; Caiazzo & Heyl 2017; Grishin & Veras 2019), and (iii) exo-moons (Payne et al. 2016, 2017). How much each class of object contributes to white dwarf pollutants remains debatable, even though the term “asteroids” has convention-
Fig. 6.— A rough breakdown of parameter space for investigations of planetary architectures around white dwarfs.
ally been adopted as a catch-all for minor planets. By analogy with the solar system, the total mass in moons can easily exceed the total mass in a main belt analogue, and the total mass of Oort cloud comets is uncertain by many orders of magnitude. Chemically, although dry asteroids and moons provide the best match to the majority of white dwarf pollutants, the mounting number of volatile-rich minor planet progenitors (subsection 2.4) suggests that relying on dry asteroids alone to represent pollutants is incorrect.

Architecture studies with zero major planets typically feature physics other than just point-mass \(N\)-body gravitational interactions, including sublimation of volatile patches on active asteroids \cite{Veras2015a}, rotational fission of asteroids due to spin angular momentum exchange \cite{Makarov2019}, the effect of Galactic tides and stellar flybys on comets \cite{Alcock1986,Parriott1998,Veras2014a,Stone2015}, capture of asteroids and comets within a gaseous disc \cite{Grishin2019}, and von Zeipel-Lidov-Kozai perturbations due to a stellar companion \cite{Hamers2016,Stephan2017}.

Although these mechanisms can succeed in polluting the white dwarf and populating an extant disc, at least one major planet \cite{Bonsor2011,Debes2012,Frewen2014,Antoniou2016,Antoniou2019,Caiazzo2017} greatly facilitates dynamical delivery, particularly when a binary stellar companion is involved \cite{Bonsor2015,Petrovich2017,Stephan2017,Stephan2018} (see Fig. 7). Circumbinary studies with one major planet \cite{Kratter2012,Veras2012,Kostov2016} have yet to feature minor planets.

Investigations with two major planets \cite{Debes2002,PortegiesZwart2013,Mustill2013,Veras2013,Voyatzis2013,Veras2017b,Veras2018a} or more allow for the possibility of (i) determining the fate of known main-sequence multi-planet exosystems, even if re-scaled \cite{Maldonado2020a,Maldonado2021} and (ii) dynamical activity due to gravitational instability amongst the planets themselves. Depending on the initial configuration, the instability between the two planets can occur at any time during the white dwarf phase. However, with two planets, only one instance of instability is possible, and usually eliminates one planet from the system through escape or collision with the white dwarf.

In contrast, studies with three major planets allow for multiple generations of instabilities \cite{Mustill2014,Mustill2018,Maldonado2020a} and secular resonance shifts due to engulfment of one of the planets \cite{Smallwood2018}. With four or five major planets, investigations can model outer solar system analogues around white dwarfs, including the future Sun \cite{Duncan1998,Veras2016a,Veras2020a,Zink2020}. As the number of major planets increases further \cite{Veras2015,Veras2016,Maldonado2021}, an emerging trend is that their tendency to linger and meander after gravitational instabilities increases with (i) total number of planets, (ii) decreasing planet mass, and (iii) increasing orbital eccentricities. Such meandering can activate previously dynamically stagnant reservoirs of minor planets,
### Some Theory Snapshots

#### Major planet perturbations
Stephan, Naoz & Zuckerman (2017)

![Diagram](image)

#### Minor planet accretion
Mustill, Villaver, Veras et al. (2018)

![Diagram](image)

#### Disc/Ring Formation
Malamud & Perets (2020a)

![Diagram](image)

#### Disc/Ring Evolution
Kenyon & Bromley (2017b)

![Diagram](image)

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Fig. 7.— Illustrative examples of planetary architecture evolution for an exo-Neptune entering the white dwarf Roche radius (upper left), exo-asteroid belts accreting onto a white dwarf in a multi-planet system (upper right), disc formation (lower left) and disc evolution (lower right). The upper left and lower rights plots are © AAS. Reproduced with permission.
potentially enhancing pollution and disc formation prospects.

3.2. Physics close to the white dwarf

An important end product of the dynamical evolution of planetary architectures during the white dwarf phase is matter (planets, moons, comets, asteroids, dust) which veers close (within several Solar radii) to the white dwarf. At this stage, several different physical effects outlined in Fig. 8 become important; the shaded regions usually involve discs or rings. This subsection will discuss these effects in a clockwise direction from the illustration, starting with tides.

All objects approaching a white dwarf will experience gravitational tides, and these can alter the orbital eccentricity and semimajor axis of large asteroids and major planets whose pericentre distances exceed the Roche radius. The tidal interaction between white dwarfs and solid bodies (Veras et al. 2019; O’Connor & Lai 2020) and gaseous bodies (Veras & Fuller 2019) reveal non-trivial dependencies on the internal structure and spin of the object. Extant discs or rings produced from minor planet destruction are unlikely to be massive enough to play a role in the tidal interaction. Hence, the presence and movement of a major planet by itself would not necessarily imply the existence of a disc or ring.

These discs and rings can be formed by a variety of mechanisms. Slow methods of forming a disc include the continuous or stochastic destruction of a collection of minor planets over time (Wyatt et al. 2014; Brown, Veras & Gänsicke 2017), the gradual accumulation of crater impact ejecta (Veras & Kurosawa 2020) and the gradual accumulation of evaporated planetary atmospheres (Schreiber et al. 2019). The one rapid formation mechanism is the tidal destruction of one large object representing either a large asteroid or major planet (Jura 2003; 2008; Jura et al. 2007; Debes, Walsh & Stark 2012; Bear & Soker 2013; Veras et al. 2014b; Rafikov 2018; Malamud & Perets 2020a,b). Potential byproducts of rapid formation is the ejection of some minor planets from the system (Rafikov 2018; Malamud & Perets 2020b), the development of significant substructure within the newly formed disc (Malamud & Perets 2020a,b) (see Fig. 7), and a size distribution of remnants ranging from dust to asteroids.

Disc formation mechanisms relying on tidal destruction typically assume that the initial orbit of the tidally destroyed object is highly eccentric; in order to survive the giant branch phases of evolution, the object must arrive at the white dwarf at a distance of at least a few au. This idea has been observationally reinforced through the likely eccentric debris orbiting ZTF J0139+5245 (Vanderbosch et al. 2020). This debris might be in the process of circularizing. Fittingly, the process of and timescale for circularizing debris has become a subject in its own right (Veras et al. 2015b; Malamud, Grishin & Brouwers 2021; Nixon et al. 2021).

The evolution of the resulting roughly circular disc or ring (Bochkarev & Rafikov 2011;
Fig. 8.— Breakdown of the literature exploring different physics close to and inside of the white dwarf; shaded regions indicate the involvement of a disc or ring.
Rafikov 2011a,b; Metzger, Rafikov & Bochkarev 2012; Rafikov & Garmilla 2012; Kenyon & Bromley 2017a,b; Miranda & Rafikov 2018; Veras & Heng 2020; Malamud, Grishin & Browers 2021; Rozner, Veras & Perets 2021) incorporates a variety of physics, partly because gas generated from sublimation or collisions mixes with the dust. Given that analytic solutions for the time evolution of this gas-dust mixture are limited, employment of numerical codes would be required for more detailed modelling (see Fig. 7 for an example evolution), especially for an individual known exosystem.

For single white dwarfs, speculation that “second-generation” planets could form from disc material (Bear & Soker 2015) was addressed by van Lieshout et al. (2018). The latter demonstrated that coagulation of second-generation minor planets is possible only in relatively massive discs with masses comparable to Io or Mercury. Formation of such massive discs is assumed to be rare, particularly because of the theoretical constraints on the masses of the minor planets in the WD 1145+017, SDSS J1228+1040 and ZTF J0139+5245 systems (see the references within Fig. 2). However, for white dwarfs in binary systems, both second-generation discs (Perets 2011; Perets & Kenyon 2013; Hogg, Wynn & Nixon 2018) as well as second-generation planets (Bear & Soker 2014; Schleicher & Dreizler 2014; Völschow, Banerjee & Hessman 2014) appear to be more plausibly common.

Magnetic fields, if present, could play a role in much of the physics that was already mentioned in this subsection. Observationally, approximately 20% of white dwarfs have kG-scale or larger magnetic fields, and about 10% have fields stronger than 1 MG (Ferrario, de Martino & Gänzicke 2015; Hollands, Gänzicke & Koester 2015; Landstreet & Bagnulo 2019). The magnetic fields in these white dwarfs could affect the evolution of major planets (Li et al. 1998; Willes & Wu 2004, 2005; Veras & Wolszczan 2019), minor planets (Bromley & Kenyon 2019) and disc material (Farihi et al. 2018a; Hogg, Cutter & Wynn 2021), and might open up a new avenue for the discovery of planetary remnants (Gänzicke et al. 2020).

The fate of all close material smaller than major planets will be accretion onto the white dwarf. In the photosphere, the sinking timescales and diffusion properties of the planetary debris crucially affect the modelling of planetary chemistry, including whether the accretion is in a “steady-state”, “increasing” or “decreasing” phase (see upper-right panel of Fig. 4). Each chemical element has a different sinking timescale (Koester 2009; Blouin, Dufour & Allard 2018), and is affected by thermohaline mixing (Deal et al. 2013; Wachlin et al. 2017; Bauer & Bildsten 2018), overshooting (Kupka, Zaussinger & Montgomery 2018; Bauer & Bildsten 2019; Cunningham et al. 2019) and horizontal, as well as vertical, sedimentation (Cunningham et al. 2021).

4. The future

White dwarf planetary science is a rapidly growing field; only one of the references in Figs. 2-4 predates 2015, and about half of all the references in Figs. 6 and 8 were written after 2015. Prospects for future discoveries are summarized in Fig. 9. A recent eight-fold
Fig. 9.— A representative set of ongoing and upcoming ground-based and space-based facilities which represent the observational future of white dwarf exoplanetary science. 

increase in the total population of white dwarfs (Gentile Fusillo et al. 2019) will help multiple ongoing and future facilities to continue characterizing photospheric chemistry, detecting dust and gas in discs and rings (Fantin, Côté & McConnachie 2020), and discovering additional minor and major planets (Perryman et al. 2014; Cortés & Kipping 2019; Danielski et al. 2019; Tamanini & Danielski 2019). Such advances will motivate a variety of theoretical studies, such as those which incorporate sophisticated global hydrodynamical simulations of circumstellar gas and dust, planet formation around the highest mass progenitor host stars (Veras et al. 2020c), the mapping of orbital architectures with nebular chemistry and exo-meteorite families (Harrison, Shorttle & Bonsor 2021), and even tracking the prevalence of plate tectonics through stellar evolution (Jura et al. 2014).

Finally, by analogy with main-sequence exoplanetary systems, one other area of increasing interest is planetary atmospheric chemistry (Gänsicke et al. 2019) and the potential for habitability around white dwarfs (Agol 2011; Fossati et al. 2012; Barnes & Heller 2013; Ramirez & Kaltenegger 2016; Kozakis, Kaltenegger, & Hoard 2018; Kozakis, Lin & Kaltenegger 2020). In fact, the relatively large radius ratio between a major planet and a white dwarf would allow for exquisite atmospheric characterization of terrestrial planets with
Fig. 10.— The required number of JWST transits to detect molecular species in the atmosphere of an Earth-like planet orbiting a white dwarf. From Kaltenegger et al. (2020). This plot is © AAS. Reproduced with permission.

JWST (Fig. 10) (Kaltenegger et al. 2020), and dynamical studies of planetary architectures (Fig. 6) predict that such planets should exist.

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