Polluted WD explainer

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1. Abstract

White dwarfs are the ultimate fate of the vast majority of stars in the Milky Way, and are the only available laboratories for probing internal compositions and refractory elements of exoplanetary material. Around 30-50% of white dwarfs show metal pollution in their atmospheres, material from Earth-like planets, giant planets, ateroid-like and Kuiper Belt-like objects, comets, icy moons, even water-rich bodies. Material deposition onto the white dwarf photosphere involves tidal disruption due to the object passing within the white dwarf's Roche lobe ($\sim 1\ R_{\odot}$), however the mechanism for orbital disruption onto star-grazing orbits is not well constrained. The degree to which the presence of a wide stellar companion contributes to pollution is not understood, and small sample sizes hinder population studies. We present the ExAO Pup Search, leveraging the power of new extreme adaptive optics instruments MagAO-X and SCExAO towards detection of new wide white dwarf - main sequence star (WDMS) systems and pollution and orbit monitoring studies of new and previously known WDMS systems. We discuss the science of white dwarf pollution, the current state of WDMS studies, how ExAO Pup Search will contribute to the field, and directions for the future of this project.

2. White Dwarf Pollution

2.1. White Dwarf Pollution as a Signature of the Post-AGB Planetary Regime

In the Milky Way ~95% of stars will become white dwarfs (Althaus et al. 2010). White dwarfs – the core of a star that remains after it has evolved through the asymptotic giant branch stage and has lost its envelope – are excellent laboratories for study of exoplanetary material compositions[1]. They are $\sim 10^5$ times as dense as the Sun, and due to this extreme gravity elements quickly stratify with heavier elements (carbon, oxygen, and [rarely] neon from core burning) sinking to the core and lighter elements remaining on the surface, typically retaining only hydrogen or helium in their photospheres (Schatzman 1958; Koester 2009; Althaus et al. 2010; Koester 2013). Sinking times for metals are on the order of 1 – 1×10^6 yr, much shorter than the cooling times of WDs (Fontaine & Michaud 1979; Koester 2009). Thus, for WD with $T_{\rm eff} \lesssim 20{,}000$ K (cooling ages 30 Myr $\lesssim t_{\rm cool} \lesssim$ 500 Myr), metals detected on their surface must have been deposited relatively recently from an external source (for WDs with $T_{\rm eff} \gtrsim 20{,}000$K radiative levitation can cause heavy materials to be lofted to the surface, Chayer et al. 1995; for older WDs carbon may be dredged up from the core to the surface and will have a Q spectral type). To date 18 metals heavier than carbon — termed "pollution" — have been discovered in WD photospheres[2], including rock-forming elements (Si, Fe, Mg, O), lithophiles (rock-loving elements found near planetary surfaces; Ca, Al, Ti), volatiles (elements found on or above planetary surfaces; C, N, P, S), and siderophiles (iron-loving elements found in planetary cores; Cr, Mn, S, Ni) (Goldschmidt 1937; Veras et al. 2016).

The source of the pollution has been well established to be from planetary material[3] rather than other sources such as the interstellar medium (Jura 2008; Zuckerman et al. 2010). The ISM as a source is inconsistent with chemical and kinematic observations (Jura 2006; Kilic & Redfield 2007; Farihi et al. 2010). Over 40 WDs are known to host dusty debris disks (Farihi 2016), some of which also contain gas (Gänsicke et al. 2006, 2008; Farihi et al. 2012; Melis et al. 2012; Wilson et al.

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[1] The first metal-enriched isolated white dwarf was recorded by Adriaan van Maanen in the 1910's (van Maanen 1917, 1919)

[2] O(8), Na(11), Mg(12), Al(13), Si(14), P(15), S(16), Ca(20), Sc(21), Ti(22), V(23), Cr(24), Mn(25), Fe(26), Co(27), Ni(28), Cu(29), Sr(38), (Veras et al. 2016)

[3] Throughout this work I use "planetary material" and "planetary bodies" to mean all substellar objects orbiting a star or white dwarf, including debris, asteroid-like objects, planets, and even up to brown dwarf masses

2014; Manser et al. 2016), and which formed after the main sequence and giant branch phases (Veras et al. 2018). Many show strong silicate emission at 10μm (e.g. Jura et al. 2009; Jura et al. 2007; Reach et al. 2009). Every known debris disk orbits a polluted white dwarf. Some (most) disks may be too optically thin to be detectable, and the frequency of bright, IR detectable disks decreases with cooling age (Bergfors et al. 2014; Bonsor et al. 2017), hinting that polluted WDs without a detected disk can still host one; Brown et al. (2017) determined that direct infall of material on parabolic orbits is a possible dynamical explanation for pollution in the absence of an IR excess. The debris-disk hosting WD 1145+017 was found to also host at least one minor planet in the process of disintegrating (Vanderburg et al. 2015). Accreted material composition is consistent with rocky material similar to the inner solar system (Zuckerman et al. 2007; Gänsicke et al. 2012; Farihi et al. 2013). Accretion of planetary material as the main source of WD pollution is firmly established by evidence.

The exact nature of pollutants remains diverse (Gänsicke et al. 2012). Jura (2008) posit pollution of gas-phase elements from tidallay disrupted asteroid-analog bodies for single WDs without observed debris disks. plantesimal accretion papers Pollution from differentiated bodies — planets — have been observed as well (e.g. Klein et al. 2010; Zuckerman et al. 2011; Melis et al. 2011). Recently, Bonsor et al. (2020) showed the Ca/Fe ratios for a fraction of WDs were consistent with accretion of a differentiated body — core-like and mantle-like material — rather than the compositions from the start of planet formation. This suggests a significant portion of pollution could be coming from fragmented planets, and that differentiation is common in exoplanetary systems. The scattering of exomoons is proposed as a source of pollution (Payne et al. 2016); the discovery of Be in a polluted WD (Klein et al. 2021) is suggested to come from icy exomoons similar to Saturn's moons (Doyle et al. 2021).

WD transiting planets (Vanderburg et al. 2020), planetesimals, and debris from tidal disruptions (e.g. Jura 2003; Vanderbosch et al. 2020; Guidry et al. 2021; Vanderbosch et al. 2021) and debris disks (Farihi et al. 2022) have been observed. The degree to which accretion is primarily from planets or asteroid-like bodies is not well understood or constrained, and constraints on the masses of accreted parent bodies is necessary to differentiate. Buchan et al. (2022) developed a framework for estimating the parent body mass using abundances for elements the vary with internal pressure (which is a function of mass), such as Cr, Ni, and Si. Veras et al. (2018) Section 3 outlines six lines of evidence suggesting planets need to exist around polluted WD single stars.

2.2. Occurrence of planetary material around white dwarfs

Around 30-50% of single white dwarfs show pollution in their optical and UV spectra (Zuckerman et al. 2003, 2010). Koester et al. (2014) found that ≈50% of WDs with 17,000 K<$T_{\rm eff}\lesssim$20,000 K were accreting planetary material. Stars $T_{\rm eff}\gtrsim$23,000 K exhibited a rapid drop off in accretion due to the luminosity being high enough to vaporize debris, and it is unclear to what degree radiative levitation plays vs accretion in the appearance of photospheric metals. They concluded that rocky planets are common around late B- and A-type stars. van Sluijs & Van Eylen (2018) found occurrence of habitable-zone Earths around white dwarfs as high as ≤46%, similar to their occurrence rate around main sequence stars.

Johnson et al. (2010) showed a correlation between host star mass and metalicity, with an increasing likelihood of hosting planets with semi-major axis (a) $\lesssim$2.5 AU with increasing mass. Similarly Bowler et al. (2010) found a higher frequency of Jovian planets interior to 3 AU for retired A stars ($1.5 \lesssim M_*/M_\odot \lesssim 2.0$) compared to sun-like stars. Given that WD progenitors are massive stars, this points to a higher likelihood of planets for WD progenitors. (However it should be noted that Yang et al. 2020 found a decreasing trend with mass for type K–F Kepler short-period planet hosts)

However it is unclear if this trend with mass holds for orbits that will survive the AGB phase (a $\gtrsim$3 – 5 AU) verify this. Nevertheless wide orbit planets around main sequence stars are common. For example, Bryan et al. 2019 found an occurrence rate of 39±7% for masses 0.5-20 $M_{\rm Jup}$ and separations 1-20 AU from radial velocity surveys; Herman et al. 2019 found $0.7^{+0.40}_{-0.20}$ planets per solar-type star on 2-10 yr periods from *Kepler* (Borucki et al. 2010); Poleski et al. 2021 observed $1.4^{+0.9}_{-0.6}$ ice giants per microlensing star with separations ≈5-15 AU from the OGLE microlensing survey.

2.3. Planetary material during and following evolution to the white dwarf phase

The orbits of outer planets around the WD progenitor expand as the star losses mass during the AGB phase (Duncan & Lissauer 1998; Adams et al. 2013). While inner planets ($\lesssim$3 – 5 AU) become engulfed during RGB and AGB expansion (Rasio et al. 1996; Villaver et al. 2014; Mustill & Villaver 2012), wider planets will see their orbits expand as the host star loses mass. The orders-of-magnitude-larger luminosity in GB phases can also contribute to orbit changes for planetesimals (Veras et al. 2015), strip planets of their atmosphere (Goldstein 1987), destroy comets and asteroids through spin up (Veras et al. 2014). Some can become unbound as their orbits expand, and many will have their orbits disrupted or excited to high eccentricities (Veras et al. 2011). Previously stable systems can rapidly become unstable during and after mass loss (Debes & Sigurdsson 2002; Duncan & Lissauer 1997; Bonsor et al. 2011; Debes et al. 2012). The presence of a massive distant planet (>300 AU) can also readily destabilize an otherwise quiet post-main sequence planetary system (Veras 2016a). In simulations of a 2-planet system destabilized due to mass loss, a wide chaotic region in phase space occurs and typically results in ejection of the lighter planet (Rasio & Ford 1996; Voyatzis et al. 2013). Indeed stellar mass loss maybe be the dominant source for free-floating planets (Veras et al. 2011). Veras & Gänsicke (2015) showed that tightly-packed multiplanet systems can remain stable well into the WD phase, with "unpacking" of the system occurring several Gyr after onset of WD phase. Changes in secular resonances due to evolving planetary system architecture from primary mass loss (Smallwood et al. 2018) and from outer bodies in the system (O'Connor et al. 2022)can drive continuous pollution onto the WD . The amount of dynamic evolution and instability depends on planet masses and mutual Hill radii (see Veras et al. 2016, for a detailed analysis of the influence of planetary architectures during post-MS evolution). Viscous spreading of disks can even generate a set of second-generation miron planets just outside the Roche limit van Lieshout et al. (2018). Whether they survive the AGB phase or formed via a second generation of planet formation (see Section 3.3.6), intact planets around WDs can find a habitable zone (due to radiation and tidal heating) at $\sim$0.2 AU for ages up to 10's of Gyr (Becker et al. 2023), posing an intriguing environment for astrobiology. More discussion on the fates of material around WDs in Section 2.5.

2.4. Science enabled by pollution studies

Polluted white dwarfs are "cosmic mass spectrometers" (Xu & Bonsor 2021). The study of post-MS planetary systems in addition to MS ones enables 1) access to surface and interior planetary body chemistry, 2) a link between planetary body formation and ultimate fate, 3) further constraints of mass-loss and radiative processes, and 4) detection of planetary bodies in extreme environments (paraphrased from Veras 2016b, Section 3).

Again and again pollution studies reveal the composition of accreted material resembles the solar system (e.g. Zuckerman et al. 2007, 2011; Jura & Young 2014; Jura 2014; Doyle et al. 2023), including Earth (Xu et al. 2014, 2019), giant planets (Gänsicke et al. 2019), asteroids (Zuckerman et al. 2003), specifically Cl chondrite asteroids (Wilson et al. 2016), icy moons (Doyle et al. 2021), Kuiper Belt analogs (Xu et al. 2017), water-rich bodies (Farihi et al. 2011, 2013; Raddi et al. 2015; Hoskin et al. 2020; Klein et al. 2021) Material is $\sim$85% O, Mg, Si, and Fe by mass, and is carbon-deficient by a factor of 10 just like the inner solar system (Jura & Young 2014). There is evidence of differentiation in accreted material as well, where bodies stratified into crust-like and core-like compositions, indicating accretion of a disrupted planet (Farihi et al. 2011; Zuckerman et al. 2011; Melis et al. 2011; Gänsicke et al. 2012; Melis & Dufour 2016; Harrison et al. 2018; Bonsor et al. 2020; Harrison et al. 2021; Johnson et al. 2022). Other studies have found asteroidal-sized bodies were better fit to observations (Jura 2006; Jura & Young 2014; Harrison et al. 2018).

Chemical abundances of volatiles in accreted material can be used to constrain the radial location of the formation of exoplanet (Harrison et al. 2018; Harrison et al. 2021). Condensation temperatures of volatile elements will affect abundance of the element. So formation location is probed by analysing the abundances with respect to the host star. Harrison et al. (2018) found pollutants originating from a wide range of locations, suggesting that scattering onto the WD is equally efficient at all radii. They also found their data best matched by extremely volatile-deficient models, suggesting that giant branch heating vaporized the outer layers before accretion. Harrison et al. (2021) found evidence of accretion by Moon- and Vesta-

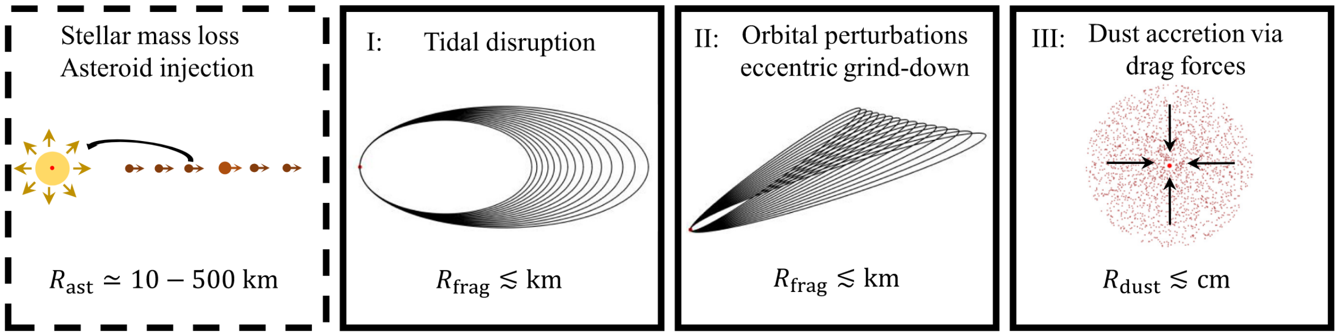

Fig. 1.— Figure 1 from Brouwers et al. 2022 illustrating the proposed roadmap for white dwarf pollution. As the star loses mass the orbits of planetesimals expand (leftmost panel, dashed border). This destabilizes the orbits and some bodies are scattered onto high eccentricity star-grazing orbits where they are tidally disrupted (panel I). The orbits are further perturbed causing collisions and grind-down (panel II). Finally drag forces circularize the orbits and material accretes onto the star (panel III).

sized differentiated objects from a variety of radial locations.

Bonsor et al. 2021 found that for a test polluted WD + K dwarf system, G200-40 + WD 1425+540, metal abundances in the white dwarf, deposited by planetary material, mostly matched the main sequence star, as expected if star and planet both formed from the same cloud material. While their uncertainties were too high to make a firm conclusion, this points to the ability of host star abundances to constrain internal compositions of rocky planets. However other studies have found planetary material abundances much different than the host star (e.g. Xu & Bonsor 2021), just as with the inner solar system.

Abundance studies reveal a vast array of diverse and complicated geology in exoplanetary systems that defy simple classification. Abundance studies have permitted estimates of rock types on extra-solar worlds, and have revealed non-Earth like silicate mantle compositions that are very different from what is found in our solar system (Putirka & Xu 2021). Bulk compositions are capable of distinguishing between Mercury-, Earth-, Moon-, and Mars-like exoplanet geology. Xu & Bonsor (2021) found such exotic exoplanet geology as to require new rock classification schemes. While other studies had found evidence of crust-like material (Hollands et al. 2018, 2021), they found only mantle-like materials.

Lithium and Beryllium abundances have also been used in cosmological and probes of star formation environments. Kaiser et al. (2021) found more Li in two white dwarfs than would be expected from Big Bang nucleosynthesis, which may be explained by accretion of planetesimal crust or by galactic nucleosynthesis. Be enrichment in WDs found by Klein et al. (2021) points to destruction of other elements by high-energy photons, implying the star and planet system may have formed in extremely high energy environments.

2.5. Material deposition onto the white dwarf

Given the short sinking times of most WDs, we expect pollution levels $\lesssim 0.1\%$ (Veras et al. 2016), but given that we see pollution fractions of 25-50%, accretion must be ongoing and occurring as we are observing it. So how is planetary material deposited on the photosphere? The main source for deposition of pollution involves numerous tidal disruptions of small asteroids (Jura 2008; Debes et al. 2012). This mechanism for depositing exoplanetary material onto the surface of the white dwarf first requires perturbation of a body's orbit into a high-eccentricity orbit with a pericenter within the tidal disruption radius of the star – the Roche radius, typically $\sim$1 $R_\odot$ ($\sim$0.01 AU, Fulton et al. 2014) – where it is subsequently broken down into smaller pieces which eventually grind down into dust and eventually deposit on the surface (Brouwers et al. 2022). This process is illustrated in Figure 1, which reproduces Figure 1 from Brouwers et al. (2022). Once material is disrupted into gas and dust disks Poynting-Robertson drag and viscous accretion become relevant; in high mass disks disks viscous spreading can even lead to formation of new planetestimals similar to the formation of moonlets at the edge of Saturn's rings (van Lieshout et al. 2018). Figure 2 reproduces Figure 1 of van Lieshout et al. (2018) and illustrates the particles and mass flow of

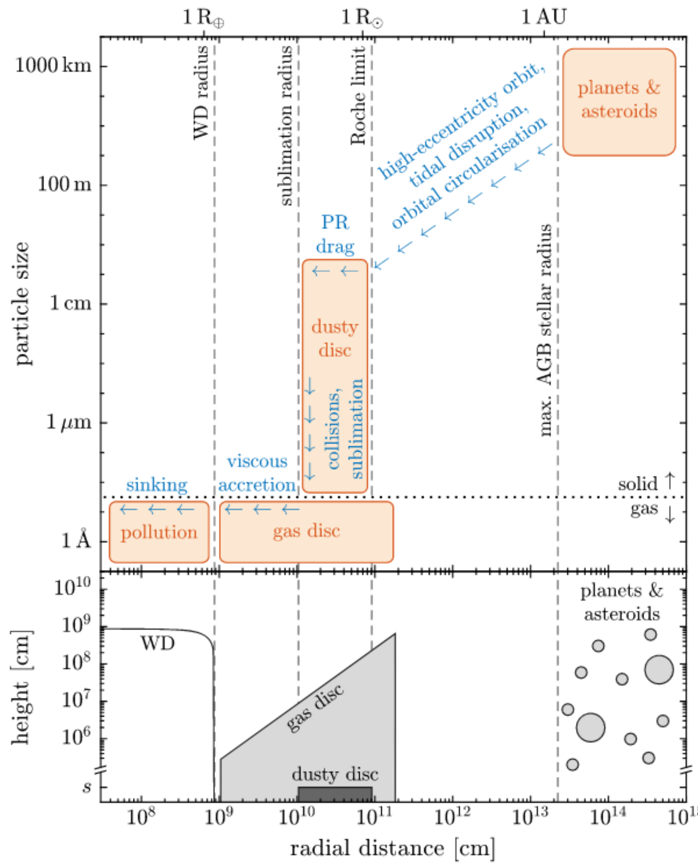

Fig. 2.— Figure 1 from van Lieshout et al. 2018 illustrating a model for the circumstellar environment around polluted WDs and material deposition onto the surface. Top panel: Particle size as a function of distance and phase. Components of the system are labeled in orange boxes; mass flow through the system is labeled in blue arrows. We see the role Poynting-Robertson drag and viscous accretion plays in facilitating accretion as small particles are closer to the WDs. Bottom panel: Geometry of system planets, gas, and dust disk.

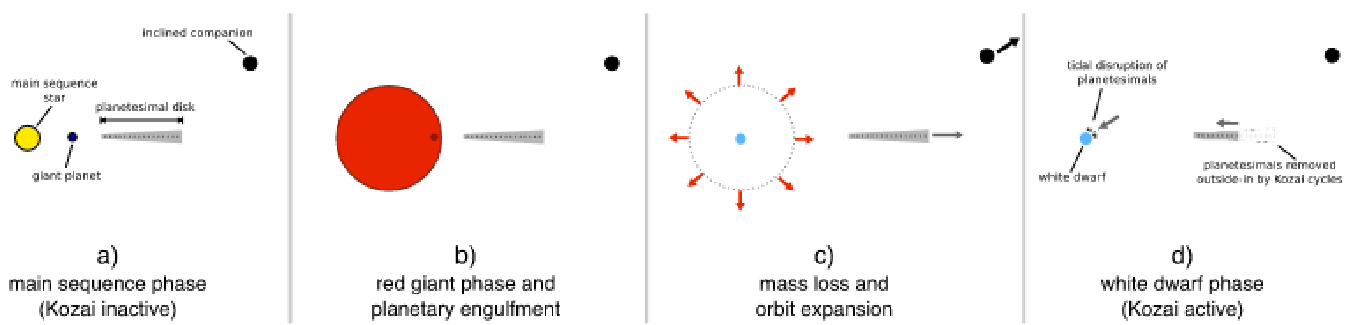

Fig. 3.— Figure 1 from Petrovich & Muñoz 2017 illustrating the vZ-K-L mechanism at play following the AGB phase for a system composed of a $2M_{\odot}$star, a Jupiter-mass giant planet on a circular orbit at 2 AU, planetesimal disk at 3-12 AU, and a $0.5M_{\odot}$binary companion at 600 AU, eccentricity 0.5, and 80° inclination. At 2 AU the apsidal precession due to GR (∼10 Myr) is shorter than the companion (∼30 Myr) so vZ-K-L are suppressed. Initially (a) the planetesimal disk is stabilized by the perturbations of the giant planet; once the planet is engulfed in the RGB/AGB phase (b), orbits expand due to mass loss (c), and disk is now subject to vZ-K-L and are driven onto the white dwarf (d).

the circumstellar environment. Pollution even in the absence of a detectable disk could point to very steep material infalling on extreme nearly-parabolic orbits directly onto the WD (Brown et al. 2017). Collisional cascades at the Roche limit form a gas and dust disk which transports materials onto the photosphere (Kenyon & Bromley 2017).

Mechanisms for perturbing material onto star-grazing orbits, however, are not well tested observationally. The primary's mass loss, multiplanet scattering, mean-motion and secular resonances from planets and stellar companions are all put forth

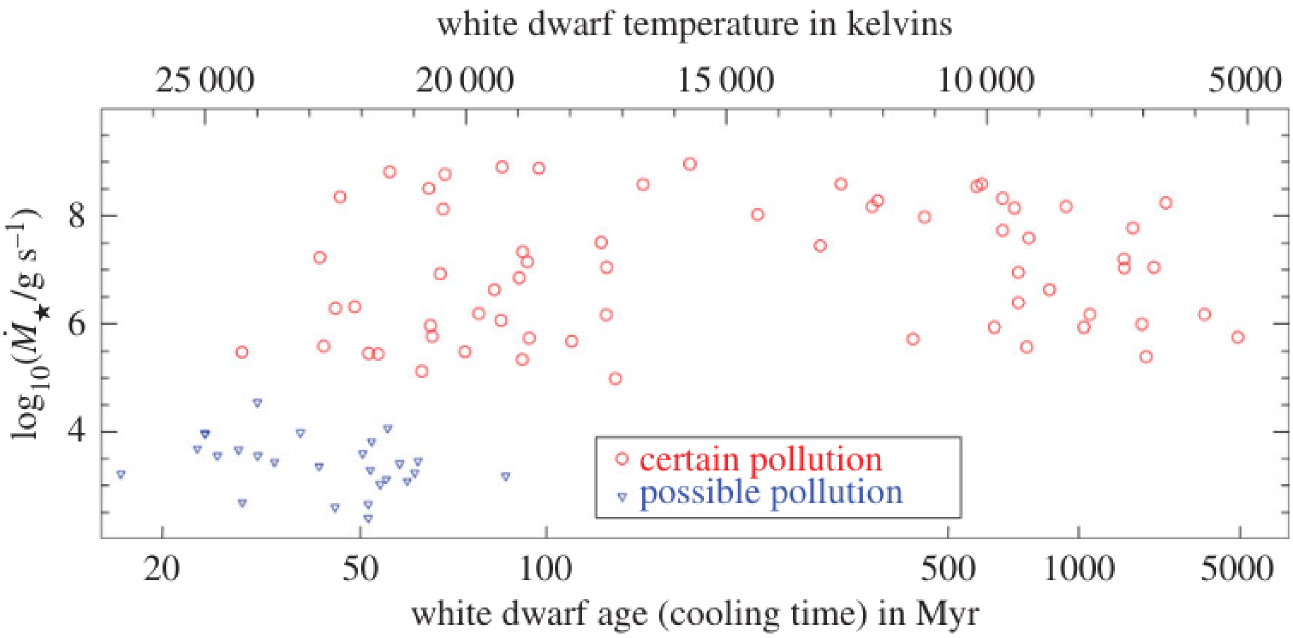

Fig. 4.— Figure 5 from Veras et al. 2016 , which reproduces Figure 8 from Koester et al. 2014 showing inferred mass accretion rates as a function of WD cooling age and temperature for 38 DAZ from Koester & Wilken (2006) and 25 DAZ observed in Koester et al. 2014. Triangles indicate upper limits. This plot shows that observed accretion rate is independent of cooling age.

as means of driving material and planets onto high-eccentricity orbits. Debes & Sigurdsson (2002) propose orbital evolution and subsequent instability driven by AGB-phase mass loss. As the star loses mass during the red giant and AGB phase, planets (< brown dwarf masses) with semi-major axis < 5AU are engulfed (Rasio et al. 1996) and will not survive (Livio & Soker 1984), but outer bodies do, and their orbit radii expand by $\sim$2-4 times due to the dropping mass of the host star citation. This causes expansion of regions of mean-motion resonances and global instability of the system (Veras et al. 2013; Mustill et al. 2014), and chaotic orbits in close circumbinary systems (Kratter & Perets 2012). The presence of a giant planet during mass loss pushes planetesimals into mean-motion resonances which can further drive them into star-grazing orbits (Debes et al. 2012).

However this mechanism predicts a steep drop-off of mass accretion rate with white dwarf cooling time, which is not supported by observations (e.g. Koester & Wilken 2006; Koester et al. 2014; Wyatt et al. 2014). Figure 4, reproducing Figure 5 of Veras et al. (2016), reports inferred mass accretion rates of observed polluted WDs and shows that these rates are independent of WD cooling age. Observations of high WD accretion fractions even at later cooling times require deposition mechanisms to be constrained by: 1) material deposition must happen for all WD cooling ages, 2) the supply of material must be a steady process, and 3) the reservoir of rocky material must be long lived (Petrovich & Muñoz 2017). **A wide companion has been proposed as one possible mechanism for WD accretion independent of cooling age.**

3. Non-interacting WD-MS systems

3.1. WD-MS evolution pathways

Stars in binaries can follow different paths as one star evolves off the main sequence depending on the initial separation of the pair. Willems & Kolb (2004) identify seven formation channels for interacting binaries – binaries in which the WD is formed after mass transfer – and non-interacting binaries – systems which do not undergo a mass transfer episode. Interacting binaries lose their envelope through mass transfer from evolving star to the companion via stellar winds or or dynamically (un)stable Roche-lobe overflow. Non-interacting WDMS systems, Willems & Kolb (2004)'s 7th formation channel, do not undergo mass transfer and evolve similarly to single stars.

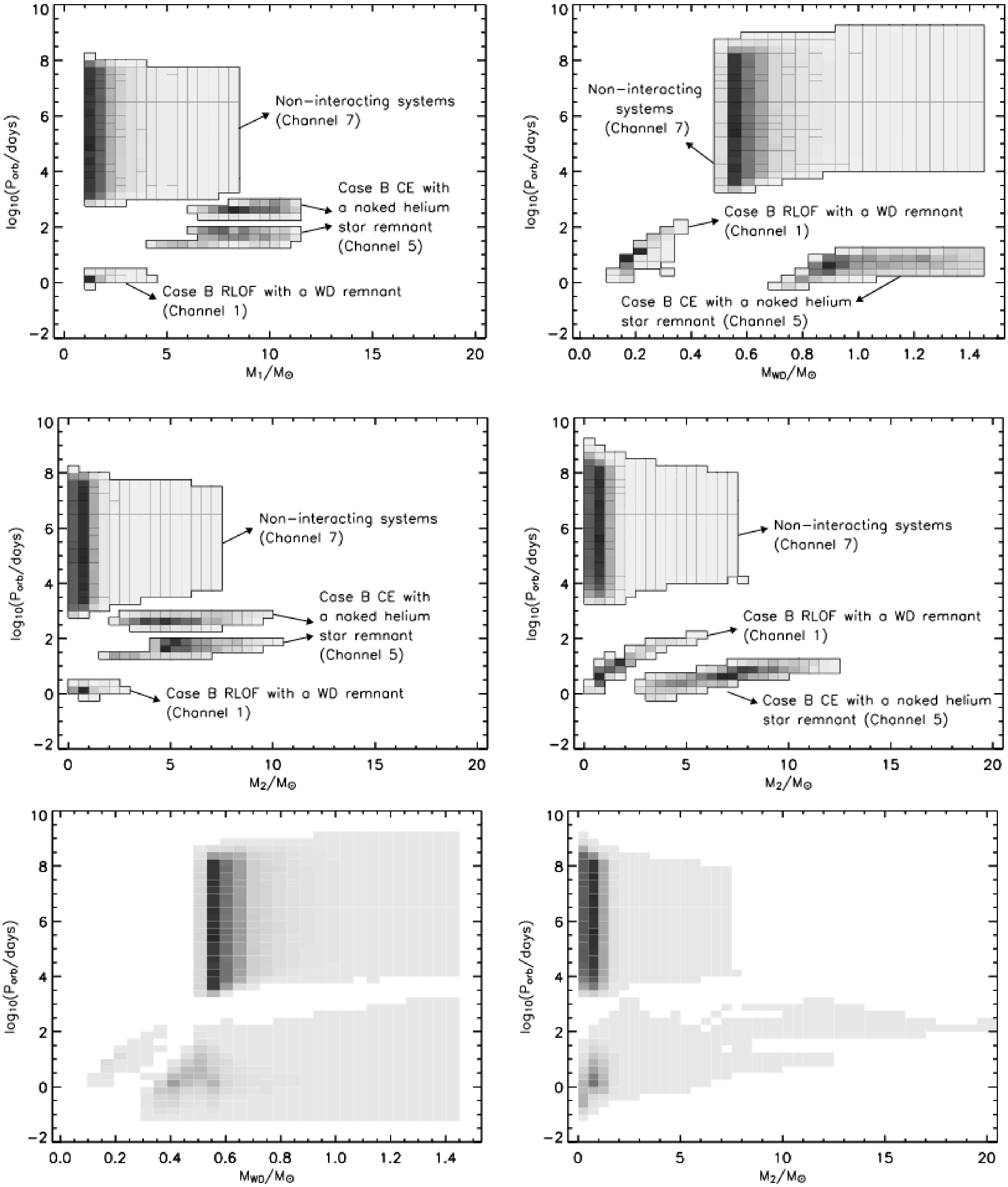

Fig. 5.— The top panels of Figure 2 (top), Figure 3 (middle), and Figure 9 (bottom) from Willems & Kolb (2004) showing parameters for WDMS binaries for several formation channels; of interest to our purposes is the non-interacting systems, channel 7. Top: mass and orbital period of the primary progenitor M_1 (left) and at the beginning of the WD phase M_{WD} (right). Middle: same as top but for the secondary star at the beginning of the primary's evolution (left) and at the start of the WD phase (right). Bottom: (mass, period) distribution for the entire population for WD mass (left) and secondary mass (right) at the start of the WD phase. The WDMS population is dominated by non-interacting (channel 7) WDMS systems with low-mass secondaries.

Figure 5 displays the top panels of Figures 2 and 3 from that paper showing the (mass, period) plane for the primary and secondary as the primary evolves to the white dwarf phase. Initial orbital periods are $\gtrsim$400 days ($\sim$ 1 yr), initial primary and secondary masses are 1–9 $M_\odot$and 1–8 $M_\odot$respectively. At the beginning of the WD phase, $M_{WD} \approx 0.5$-$0.6\ M_\odot$, $M_2 \lesssim 2\ M_\odot$. Figure 5 (bottom) shows the distribution of WD mass and secondary mass vs period for the entire population through all 7 formation channels. This distribution is clearly dominated by the non-interacting channel, with $M_{WD} \lesssim 0.8\ M_\odot$and companions $M_2 \lesssim 2\ M_\odot$. **This motivates probing this population via detection methods amenable to wide companions on long orbits, particularly high-contrast imaging**.

3.2. S-Type Planets in Binaries

Multiple star systems are an extremely common outcome of the star formation process, especially for higher-mass stars (Moe & Di Stefano 2017). But what is known about the influence of wide binaries on planet formation and evolution? Does material form and remain around one star in a wide binary — "S-type", as opposed to "P-type" (circumbinary) planets — throughout stellar evolution to eventually be deposited onto the white dwarf?

As of this writing, there are 318 S-type planet hosting stars in the NASA Exoplanet Archive[4] out of 3943 total planet hosting stars, with separations from $\sim$20–400 AU; 8% of the known planet hosting stars have wide binary companions (compared to just 1% being circumbinary planets). Christian et al. (2022) identified 67 visual binaries hosting *TESS* (Ricker et al. 2015) objects of interest (TOI) from the El-Badry et al. (2021) catalog of visual binaries in Gaia ERD3, with separations 50–50,000 AU; $\sim$1% of total number of TOI-hosting stars. Ziegler et al. (2020) found 123 stellar companions within $3''$of 117 TOI hosts, out of 542 TOI hosts they searched. None are closer than $\sim$20 AU (see also Eggenberger et al. 2004)

The S-type planet occurrence rate decreases with closer binary star separation. In their investigation of *Kepler* planet hosts, Kraus et al. (2016) found fewer binary systems (with projected separation $<$ 50 AU) than expected from field binary populations, inferring that planet occurrence was suppressed in closer binary systems. A similar suppression of planet occurence was reported by Wang et al. (2015) for *Kepler* planet hosts, Matson et al. (2018) for *K2*, and Ziegler et al. (2020) for *TESS*. Moe & Kratter (2021) synthesized observational occurrence rates into a model for which separations $<$1 AU fully suppress planet formation, separations $>$200 AU have no suppression, with a decreasing planet occurrence with binary separation in between, shown in Figure 6. So, while binaries closer than $>$200 AU do suppress planet formation, there is still much of parameter space for S-type planets to form.

3.3. The influence of wide stellar companions on planets during stellar evolution

3.3.1. The companion may drive instabilities before reaching the WD phase.

If S-type planetary systems form, the influence of the companion may destabilize and/or eject planets before the star evolves off the MS. Zuckerman (2014) used polluted WDs to conclude that for A- and F-type stars, a stellar companion $\lesssim$1000 AU suppresses formation and/or long term stability of planetary systems. Since this is much wider than the 200 AU estimated by Moe & Kratter (2021), this implies that planets that make it through the formation phase aren't necessarily surviving to the WD phase. The mechanisms for driving material onto the WD — Kozai-Lidov, EKL, Galactic tidal orbit evolution, stellar flyby orbit evolution, etc. — are also in play during the MS phase. (However the timescales for galactic tidal and stellar flyby orbit evolution are on the scale of Gyr, which may be similar to or exceed the lifetime for more massive WD progenitors, Kaib et al. 2013). Mean motion resonances with the companion's orbit define regions for which S-type orbits are (un)stable (Holman & Wiegert 1999; Pilat-Lohinger & Dvorak 2002). Planet migration in binaries is evoked to explain short-period massive planets (e.g. Eggenberger et al. 2004). Haghighipour (2009) Eqn 1.1 describes the critical

[4] https://exoplanetarchive.ipac.caltech.edu/

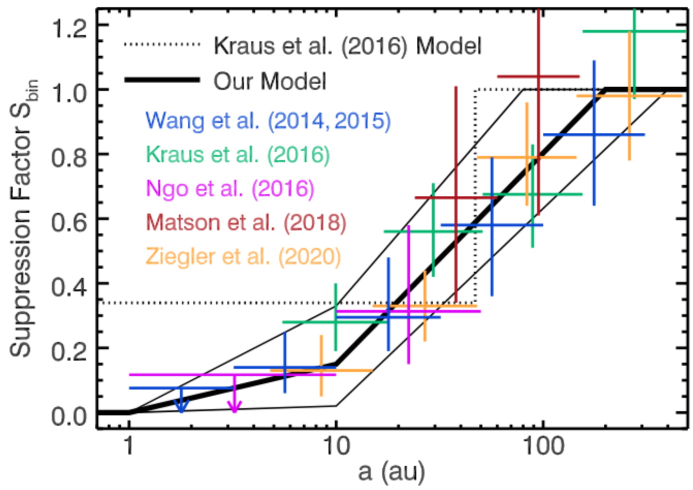

Fig. 6.— Figure 3 from Moe & Kratter 2021 showing the binary planet suppression factor $S_{\rm bin}$ as a function of binary separation. Observational occurrence rates from Wang et al. (2014, 2015); Kraus et al. (2016); Ngo et al. (2016); Matson et al. (2018); Ziegler et al. (2020) shown as marked. Their model is given by the thick black line. Binary separations $<$1 AU fully suppress planet formation, separations $>$200 AU have no suppression, with a decreasing planet occurrence with binary separation in between.

semi-major axis for which an S-type planet can remain stable as a function of binary eccentricity and mass ratio (from Rabl & Dvorak 1988; Holman & Wiegert 1999).

The environment around the primary can dynamic with many variables influencing long-term stability that are difficult to fully model. While it appears that planetary material is suppressed before making it to the WD stage, the presence of polluted WDs with wide stellar companions indicates some material survives to be accreted.

3.3.2. The companion orbit expands and may become highly eccentric

While orbit perturbation by planets in a multiplanet system may disrupt bodies at later times (Maldonado et al. 2020a,b, 2021, 2022), the influence of a wide stellar binary companion may drive pollution with or without the presence of planets in the system. The parameter space for understanding the role of a wide companion in pollution is broad.

As the primary star loses mass, the radius for stable orbits around the primary decreases as planets and the secondary star orbits expand, pushing previously stable planet orbits into regions of chaotic orbits where planet-planet collisions, planet-star collisions, ejections, and even planets hopping from primary to secondary are possible (Kratter & Perets 2012). The expansion of the companion's orbit and decrease in total system mass as the primary enters the white dwarf phase also makes the companion more susceptible to orbital evolution due to the influence of Galactic tides (Bonsor & Veras 2015; Hamers & Portegies Zwart 2016). The secondary's orbit can be perturbed externally into high eccentricity states on cycles with periods of a few Gyr, with close periastron passages to the primary by stellar flybys, supernovae, and the influence of the Galactic gravitational tide (Heisler & Tremaine 1986; Brasser 2001; Fouchard et al. 2006; Veras & Evans 2013; Veras et al. 2014; Kaib et al. 2013; Correa-Otto & Gil-Hutton 2017; Hamers 2018; Bazsó & Pilat-Lohinger 2020). During a close periastron, the secondary may perturb the orbits of planetary bodies into star-grazing orbits with high eccentricity (Bonsor & Veras 2015).

Veras et al. (2017) determined a critical binary separation for which instability of a multi-planet system is triggered at any point in stellar evolution during the giant branch and white dwarf phases. They find that a star with a stellar companion separated by $\gtrsim 7\times$ the outer planet's separation will retain a stable planetary system throughout all stages of stellar evolution. Veras et al. (2017) Figure 3 provides predictions which can be compared to observed systems.

3.3.3. The companion may drive Kozai-Lidov oscillations

von Zeipel-Kozai-Lidov (vZ-K-L) (von Zeipel 1910; Kozai 1962; Lidov 1962) oscillations can push bodies into high eccentricity and star-grazing orbits (Hamers & Portegies Zwart 2016; Mustill et al. 2022). Hamers & Portegies Zwart (2016) showed that this mechanism is consistent with observations for cooling times 0.1–1 Gyr, but cannot explain high pollution fractions <0.1 or >1 Gyr, nor pollution fractions $\gtrsim 0.2$ which have been observed.

Stephan et al. (2017) showed that mass loss during the AGB phase enhances the strength of the Eccentric Kozai-Lidov (EKL) eccentricity excitations. They find that if a multi-planet system is tightly packed, EKL-induced high eccentricities will be mostly supressed by mututal gravitational influence; however in the case of non-tightly packed planets or small objects such as asteroid belts, EKL excitations should occur and cause orbit crossings, scattering, and collisions. They predict that WDs polluted by planets or KBO-like objects will have companions consistent with distributions shown in Figure 7, namely large separations and low companions masses. They also note that the influence of galactic tides is most relevant for binaries with semi-major axis a $\gtrsim$ 500 AU, while EKL evolution is effective at closer separations (a $\lesssim$ 500 AU). WD 1856+534 b (Vanderburg et al. 2020), a Jupiter-sized transiting planet at a = 0.02 AU, has a wide (1500 AU) M-dwarf binary pair companion, indicating Kozai migration or EKL is not ruled out as a possible explanation for its current separation (Muñoz & Petrovich 2020; Stephan et al. 2021; O'Connor et al. 2021, ; discussed further in Section 3.3.5). Stephan et al. (2021) also proposes EKL for a similar close ice giant planet, WD J091405.30+191412.25 b (separation=0.07 AU, Gänsicke et al. 2019; Veras & Fuller 2020; Zotos et al. 2020), even though no companion has been found; they place an upper limit of $\sim$0.075-0.086 $M_{\odot}$for a companion based on non-detections in observations of the system. Muñoz & Petrovich (2020) estimate a $\mathcal{O}(10^{-3} - 10^{-4})$ occurrence rate for Kozai-migrated planets.

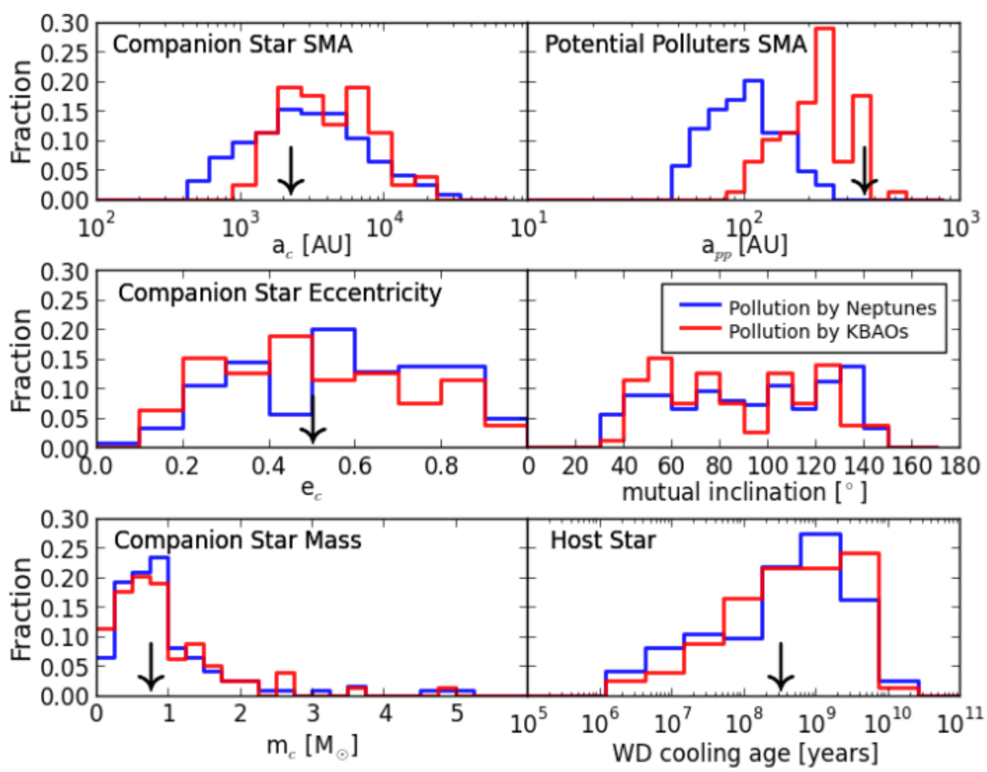

Fig. 7.— Figure 4 from Stephan et al. 2017 showing the distribution of orbital parameters expected for a WD polluted by the Eccentric Kozai-Lidov (EKL) mechanism. Likelihood distributions for Neptune-like (blue) and Kuiper Belt object analogs (KBO, red) are shown. Arrows indicate parameters for the WD 1425+540 system. They predict that WDs polluted by planets or KBO-like objects will have companions consistent with these distributions.

3.3.4. The companion may drive secular resonances

Secular resonances can arise even in binaries wider than 1000 AU if a giant planet is present around the primary (Bazsó & Pilat-Lohinger 2020). Petrovich & Muñoz (2017) propose that instabilities that drive material into star-grazing orbits are secular (not scattering or mean motion resonances) initiated at the end of the AGB phase once the star has engulfed previously-stabilizing inner planets, which addresses the three criteria outlined in Section 2.5. They invoke the presence of a wide (>100 AU) stellar companion and the vZ-K-L mechanism as a scenario where these instabilities can arise (although they note that their proposed mechanism is generalizable to other scenarios of secular excitation). As long as there are nearly coplanar planetary bodies, they are protected from the tidal potential of the companion; however these stabilizing inner planets are engulfed by the expanding star during the AGB phase (Mustill & Villaver 2012). Planetary engulfment causes the Laplace radius — the radius within which an orbit is stable — to decrease (Petrovich & Muñoz 2017 Eqn 3, 5), exposing remaining bodies to the companion's tidal influence (depicted in Figure 3). The timescale for operation of this mechanism will vary with outer companion mass and separation. Mass loss from the binary and he influence of galactic tides on its orbit would enhance the vZ-K-L mechanism, while the presence of multiple planets may shield planetesimals at larger distances.

Smallwood et al. (2018) investigated the role of changing secular resonances, particularly the ν_6 resonance, on WD pollution. As the primary loses mass, the ν_6 resonance shifts outward, causing previously stable bodies to undergo secular resonant perturbations increasing tidal disruptions and debris disk formation. These perturbations by secular resonances can last much longer than the cooling age and provide an age-independent mechanism for sustained pollution. Secular resonances from (sub)stellar companions can operate even on close ($\lesssim$ 1000 AU) coplanar orbits where disruption from vZ-K-L or galactic tides aren't at play. They found that this mechanism can cause pollution for systems with binary separation $<$ 400 AU.

O'Connor et al. (2022) expanded on Smallwood et al. (2018) with secular evolution of test particles with a giant planet ($\gtrsim$ 10 M$_{oplus}$) at $\gtrsim$ 10 au for up to 10 Gyr of system evolution. They found that the planet can excite high eccentricites in asteroid analogs across the whole range of WD cooling ages. They found an even higher accretion rate onto the WD than in Smallwood et al. (2018).

3.3.5. The companion may push surviving planets to close WD orbits

Kratter & Perets (2012) found that mass loss from the primary leads to situation where planets can hop from primary to secondary, and dissipation of energy in the envelope of the AGB phase can lead to planetary capture on close orbits, especially for massive planets and brown dwarfs. They predict we could find planets on closer orbits to WDs than they would have been on to survive engulfment, and likely in the habitable zone of the WD. They note that future surveys may find planets on the edge of stability around the MS star of a WD-MS binary, planets closer to the WD than would have been to survive AGB phase, and planets on the edge of stability for WD-WD binaries.

One such system is WD 1856+534 (hereafter WD 1856). The WD planet WD 1856 b, with a 1.4 day period, is much closer than it must have been previously to survive stellar evolution. WD 1856 is a companion to a pair of M dwarfs, G 229-20 AB, at $\sim$1000 AU separation. Vanderburg et al. (2020) found that the pair could induce vZ-K-L cycles in the planet's orbit, but that those timescales are too slow ($\gtrsim$ 100 Myr) with only small (e $\sim$ 0.1) oscillations, and concluded that on their own they could not be responsible for putting the planet on a close-periastron orbit. However they were not able to rule out the possibility of dynamical instabilities caused by galactic tides, which perturb the wide WD binary (for systems $\gtrsim$1000 AU, as in this system) and lead to a close approach with disruption of planets around the WD. Given the old age of this system and the presence of the wide companions possibly in an orbit for which galactic tides are relevant (as determined by Bonsor & Veras 2015), this mechanism could plausibly be at work in this system. However this is not the only plausible explanation they give for the planet's current orbit.

3.3.6. *The companion may facilitate a second generation of planet formation*

The presence of a main sequence companion could facilitate 2nd and even 3rd generation planet formation. Perets (2011) propose that as the primary evolves to the AGB phase, lost material could form a disk around the MS secondary from which a new generation of planet formation may occur. These planets would be enhanced in metals compared to first generation planets, and may be distinguishable observationally. Then as the secondary evolves through the AGB phase, mass lost may form a disk around the primary, now a WD, from which a 3rd generation of planet formation could occur.

This mechanism provides several observationally testable predictions. Evolved binaries may show different frequency of hosting planet systems than MS binaries with similar properties. Planet hosting WDs may be more likely to be in multiple systems than singles. Also polluted WDs, if polluted by later-generation planets, may be more likely to have a WD companion. Planets in orbital phase-space inaccessible to first-generation planets might be a signpost of 2nd generation formation. Stars showing evidence of accretion from a companion could host 2nd generation planets. Second generation planets could form even in metal-poor environments, motivating searches for WD companions to planet-hosting metal poor stars and comparison of planet-star metallicities as a signpost for 2nd generation formation. The 2nd generation disk around the MS star might to be aligned with the WD binary orbit, since it is mass donated from the WD progenitor, motivating studies of angular momentum vectors of WDMS orbits and disks around MS companions, if observed.

3.4. Is the pollution in a WD with a MS companion from planetary accretion?

The presence of a main sequence companions raises the possibility that the pollution could be deposited by stellar winds from the companion. Debes (2006) found that for WDMS systems with a$<$0.02 AU stellar winds plausibly explained observed accretion, however did not explain wider systems. Zuckerman (2014) found no difference in pollution rates for WDs in binaries with a$>$1000 AU compared to single stars.

Veras et al. (2018) sought to define the critical separation for which pollution must come from the planetary regime instead of being fully explained by companion winds. They determine a critical separation for which pollution can be interpreted as being from a planetary system, which is a function of the MS companion's and WD's radii, and the WD/MS mass ratio, computed from Eq 12-15. In Figure 8 we show Veras et al. (2018) Figure 3 plotting the inferred accretion rates from stellar winds onto the WD. The dark line marks the critical boundary above which pollution can be attributed to planetary accretion. Also plotted are the computed wind accretion rates for three sets of observed WDMS systems. If the measured accretion rates of these white dwarfs exceed the values plotted here, it can be interpreted to originate from a planetary system.

3.5. Observational picture of non-interacting WD-MS binaries

3.5.1. *Sirius-Like Systems*

Holberg et al. (2013) list 98 known "Sirius-Like Systems" (SLS) composed of a multiple system containing a white dwarf with a more-luminous K-type or earlier companion(s), as opposed to WD + M systems where the WD is frequently the more luminous member and are frequently detected due to the optical colors even if they are unresolved. Of these six are known to be polluted (as denoted by "Z" spectral type), comprising 6% of the sample[5]. Table 1 of that paper lists the properties of the 98 SLS systems. Since Holberg et al. (2013) 7 new SLS systems have been discovered, listed in Table 1; none are known to be polluted as yet.

Of all 68,374 known white dwarfs in the Montreal Database (Dufour et al. 2017) at the time of this writing, 1919 are

[5]this is not comparable to the pollution rates of single WDs however since it is not known if all were observed for pollution

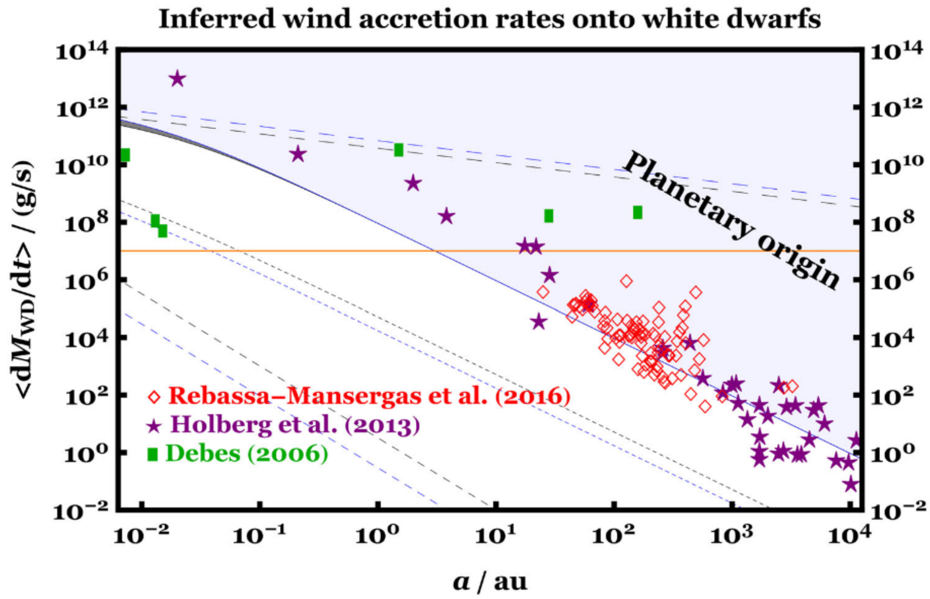

Fig. 8.— Figure 3 from Veras et al. 2018 showing the inferred accretion rates from stellar winds onto the WD as a function of separation. The dark line marks the critical boundary above which pollution can be attributed to planetary accretion. Also plotted are the computed wind accretion rates for three sets of observed WDMS systems from Debes (2006); Holberg et al. (2013); Rebassa-Mansergas et al. (2012). If the measured accretion rates of these white dwarfs exceed the values plotted here, it can be interpreted to originate from a planetary system.

Table 1: New SLS discoveries since Holberg et al. (2013)

Name	SpT	Ref
HD 114147 AB	G5 + D	Crepp et al. (2013); Matthews et al. (2014)
HD 218572 + WD 2307-691	DA + K3	Holberg et al. (2016)
BD+68 1027	G5 + DA	Kong et al. (2018)
REJ0702+129	K0IV/V + DA1.4	Kong et al. (2018)
BD+80 670	G5V + DA6	Kong et al. (2018)
HD 169889 AB	G9V + D	Crepp et al. (2018)
HD 19019 + WD 0301+059	G0V + DXP	(Landstreet & Bagnulo 2020)

indicated as polluted (3%), and 22 of those are recorded as being multiple systems (0.03% of total WD population), and all 22 are close interacting binaries. Zuckerman (2014) predicts that pollution should be low in binaries because material is disrupted throughout the stellar lifetime. Bonsor & Veras (2015) estimate that only ∼a few percent of any polluted white dwarf sample will have the orbital parameters and surviving planetary material mass to be experiencing pollution through the wide binary mechanism. Given high fraction of white dwarfs exhibiting pollution, the binary mechanism will only ever be a minor contribution. Hamers & Portegies Zwart (2016) found pollution consistent with small pollution fractions within t_{cool} ∼0.1–1 Gyr, but that this mechanism did not reproduce high pollution fractions (<0.7) in this range, nor pollution fractions outside those cooling ages. With small sample sizes of both binary and single polluted white dwarfs, it is difficult to make any meaningful comparison. It remains plausible that the binary mechanism makes a contribution to white dwarf pollution a the level of a few percent.

Observational searches for cool white dwarfs in SLS is critical to providing observational tests to the contribution of wide companions to WD pollution, and understand the role wide binaries play in planetary system evolution at the end stages of the star's lifetime. There are currently no observational samples sufficiently large enough to assess if the pollution rates of WDs in multiples is different from single WDs. Additionally, SLS provide key tests of the WD initial-final mass relation (e.g. Liebert et al. 2005; Catalán et al. 2008). Holberg et al. (2013) also notes that searches based on UV excess luminosities can overlook non-DA WDs and cooler WDs that are weaker in the UV due to photospheric opacities and heavier elements blocking UV flux. **The fainter nature of the WD companion to a K and earlier type star motivates searches with high-contrast capable imagers or ground-based extreme adaptive optics (or space-based) and high spatial resolution.**

3.5.2. *The "missing white dwarf" problem*

Another WDMS open question besides pollution is the so-called "Missing White Dwarf" problem. Holberg et al. (2013), in their paper entitled "Where are all the Sirius-Like Systems?", cataloged all known SLS at the time. In Figure 2 they show that there are 11 SLS $\leq$ 20 pc, while each subsequent shell of the same volume contain on average 1.2 SLS, implying that there are "missing" WDs which have not been detected in the vicinity of our Sun. Katz et al. (2014) found that the luminosity function of WDs within 20 pc from Holberg et al. (2008) indicates an observational bias for WDs in WDMS at the faint end. The luminosity function of WDs with MS companions agrees with that of single WDs and with theoretical predictions at the bright end ($M_V < 11.5$) and is consistent with the high multiplicity fraction of high-mass stars, however is significantly discrepant from single WDs and theory at the faint end (see Katz et al. 2014, Figure 1). They speculate that as many as 100 WDs may be hiding in the glare of their MS companion within 20 pc.

Common proper motion (CPM) studies have been conducted with *Hipparcos* (Gould & Chanamé 2004; Tokovinin & Lépine 2012) and Gaia (El-Badry et al. 2021; Hartman & Lépine 2020), and subsequent Gaia data releases including more acceleration measurements will help shed light on new systems. Rebassa-Mansergas et al. (2021) selected candidate WDMS systems within 100 pc from Gaia photometry, which gives a promising target list, however the MS component is more likely to be $\sim$M type because of the dominance of the WD luminosity, and none of them are closer than 40 pc. Hollands et al. (2018) do not detect any new unresolved WDMS systems within 20 pc with Gaia photometry. Astrometric signals can also guide searches through long term accelerations (Brandt 2018, 2021; Kervella et al. 2019, 2022) and common proper motion pairs (El-Badry et al. 2021) (however no CPM candidates in El-Badry et al. 2021 are closer than 40 pc). So the Katz et al. (2014) estimation of as many as 100 missing WDs in the local 20 pc volume seems high, as it is reasonable to assume many of them would be found by now. Nevertheless the observational bias against faint WDs in MS systems is reasonable and likely at play.

Katz et al. (2014) estimates a typical WD has a contrast of $\Delta V \approx 9$ (flux contrast $\approx 10^{-4}$) to a Sun-like star and thus is difficult to detect at the $\sim 1''$ separation of a typical SLS placed at 20 pc. However with extreme adaptive optics high-contrast ground based imaging systems this is no longer a challenging observation as these instruments routinely achieve 10^{-4} contrasts at $1''$separations. **High-contrast imaging is an essential tool for addressing the "Missing WD Problem".**

4. The ExAO Pup Search

We are leveraging the power of the new extreme adaptive optics instruments MagAO-X and SCExAO towards this problem with a survey called TheExAO Pup Search: The extreme AO non-interacting white dwarf-main sequence binary system survey[6]. The Pup Search has three main objectives:

1. Detect new non-interacting WDMS binary systems with MagAO-X and SCExAO and observe new systems for pollution with VIS-X and HST

2. Monitor orbits of new and previously known resolved WDMS system to determine prevalence of high-eccentricity orbits of MS companions for polluted WDs and compare to estimated orbital parameters for the binary to be influencing

[6]The name is a reference to the first known wide White Dwarf- Main Sequence system, Sirius AB discovered in 1844 by Friedrich Bessel when he observed changes in the proper motion of Sirius (Bessel 1844), first observed by Alvin Graham Clark (Flammarion 1877), and confirmed as the second ever known WD via its spectrum obtained by Walter Adams (Adams 1915). Since Sirius A is the "Dog Star", Sirius B was nicknamed "The Pup"

pollution, such as those in Stephan et al. 2017 and Veras et al. 2017 Fig 3.

3. Determine pollution rates for WDMS systems compared to single WDs, and as a function of cooling age and compare to estimates such as Veras et al. (2018)

We plan to grow the sample size of non-interacting white dwarf-main sequence binaries and produce observational tests of the role of wide companions on white dwarf pollution. As a byproduct we will also be contributing to the missing WD problem by identifying new WDMS systems in the local region.

MagAO-X is well suited to this science case. MagAO-X is built for extreme high contrast imaging for detecting the nearest exoplanets in reflected light, mainly Proxima Centauri b. Contrasts needed for that science are on the order of 10^{-7}; contrasts needed for white dwarf companions, depending on mass and cooling age, are on the order of $10^{-4} - 10^{-2}$, and are easily reached in relatively short observations. While much exoplanet direct imaging is carried out in mid-IR due imaging planets in blackbody emission, MagAO-X is optimized for optical and near-IR wavelengths, where white dwarf contrasts to main sequence stars are much lower due to their high UV luminosity. There is an inner working angle advantage to working in optical as opposed to infrared as well, as the fundamental length scale for direct imaging, λ/D $\approx$FWHM of central Airy pattern core, scales with wavelength. MagAO-X achieves a high Strehl ratio — a quantification of the amount of starlight contained in the PSF core compared to wings — in optical wavelengths compared to other adaptive optics instruments. MagAO-X is also equipped with a high-resolution spectrograph, VIS-X, to leverage the power of the superior optics for spatially resolved spectra. While optical pollution features in white dwarfs are less common and harder to detect than UV, VIS-X will complement planned UV HST spectra.

SCExAO/VAMPIRES is also well suited to this science case. In addition to the ExAO benefits listed above, the newly-available 4-color imaging mode is essential for quickly characterizing new systems, including temperature measurements, with minimal observational overhead. Observing with both MagAO-X and SCExAO opens up the survey area to both northern and southern tagets.

4.1. WD+AGFK binaries target list for new discoveries

As shown in Figure 5, non-interacting WDMS are expected to have companions $M_2 \lesssim 2\ M_{\odot}$, so we will prioritize spectral type A and later. Our initial previously-unknown "dog and pup" systems target list is drawn from Ren et al. (2020). Most WDMS surveys have focused on WD companions to M stars due to the ease of identification from optical colors and spectra in SDSS (Raymond et al. 2003; Silvestri et al. 2006; Rebassa-Mansergas et al. 2012; Parsons et al. 2012). They are also typically focused on close and post-common envelope binaries as progenitors of Type 1a supernovae. As part of the White Dwarf Binaries Pathway Survey (Parsons et al. 2016), Ren et al. (2020) identified 775 WD+AFGK candidates from Gaia DR2 and TGAS, crossmatched with GALEX FUV selection criteria, and measured radial velocities for 275 of them, with the goal of identifying the ones most likely to be close binaries. Out of 151 systems with multiple RV measurements, they identified 23 close binaries, discarding 128 systems identified as wide binaries for us to pick up. From their sample, we identified 34 within the RA/Dec and magnitude range accessible with MagAO-X.

4.2. Long term orbit monitoring

Holberg et al. (2013) lists 98 SLS, of which $\sim$70% had been previously resolved in HST imaging. Table 2 of that work gives orbital properties (semi-major axis, period, mass estimates, and orbital velocities) for much of these, however orbital parameters (eccentricity, inclination) were not measured and averages and assumptions were made. These are prime targets for follow up for long-term orbit monitoring for things like eccentricity and inclination constraints, particularly the ones known to be polluted.

4.3. Other sources of targets

Rebassa-Mansergas Gaia 100pc sample - which ones are potenitally accesible? Rebassa-Mansergas 2019 WDs w IR excess in Gaia sample Rebassa-Mansergas 2012 SDSS catalog Holbger 2013 sample How to use Gaia? COPAINS (Fontanive et al. 2019)

As noted in Holberg et al. (2013), searches targeting UV excess can overlook cooler and non-DA WD companions due to lower UV fluxes. For these targets, we can build upon work developing target lists for planet and brown dwarf companions using astrometric signals. Acceleration between *Hipparcos* (Perryman et al. 1997; van Leeuwen 2007) and *Gaia* (Gaia Collaboration et al. 2016) proper motions points to an unseen companion; several reductions and catalogs have been produced with the likeliest objects to host hidden companions accessible by direct imaging (e.g. Brandt 2018; Kervella et al. 2019; Brandt 2021; Kervella et al. 2022). Substellar companion hunters prioritize young stars where substellar companions will be bright in IR. Instead, WD companions can be hunted in older, overluminous stars with significant accelerations giving favorable masses for WDs (M_{WD} $\sim$0.1-1 $M_\odot$, with the most typical WD mass being M_{WD} $\sim$0.6 $M_\odot$, Kleinman et al. 2013)

4.4. Directions for the future

Detection of wide giant planets around polluted single WDs. O'Connor et al. (2022) determined that giant planets $\gtrsim$ 10 au can provide a source of secular chaos driving material onto the host star across all cooling ages. **This motivates observational searches for giant planets around polluted white dwarfs**. Schreiber et al. (2019) reported evidence that more than half hot WDs ($\gtrsim$ 20,000 K) have giant planets on 10 – 100 AU scales. Direct detection is difficult however. Their host WDs are especially faint at red wavelengths so IR searches are feasible, although depending on the age of the planet they may be especially cool with low luminosities even in IR. Another potential avenue is to detect the planets in light reflected from the host WDs. Reflected light imaging of exoplanets is still prohibitively hard for current instruments, but MagAO-X is currently pushing into regimes for detecting Proxima Centauri b in reflected light. The follow-on instrument GMagAO-X for the Giant Magellan Telescope promises to detect many nearby exoplanets in reflected light. So this ability is right around the corner, and detection of planets around polluted WDs is possible and should be a scientific priority for these instruments.

O'Connor et al. (2022) call out two potentially strong candidates for direct detection of giant planets, SDSS J122859.93+104032.9 (a.k.a WD 1226+110) and WD 1145+017. SDSS J1288+1040 (SpT DA, T_{eff} 23,5000 K Dufour et al. 2017, age <1 Gyr, M_{WD} = 0.705 $M_\odot$, Koester et al. 2014 is at 128.81 pc; a planet at 10 AU would have an angular separation of $\sim$80 mas, which is accessible to MagAO-X/SCExAO. They estimate a planet-star contrast of 10^{-4} required for detection in NIR, which is definitely achievable with MagAO-X/SCExAO. WD 1145+017 (SpT DBZA, T_{eff} 14,500K) is 145 pc, making a 10 AU planet have an angular separation of $\sim$70 mas. Both are accessible to MagAO-X and SCExAO in northern spring, although both are higher elevation at Mauna Kea. The LBTI could be good for this work as well with its high resolution at long wavelengths ($\sim$10 μm) where WDs will be faint but planets brighter. Currently there are $\sim$ 200 polluted WDs in the Montreal database less than 200 pc distant. This is very doable.

30-m class telescopes.

5. Conclusion

White dwarf pollution is a crucial component for fully understanding the exoplanet picture, as it is the only probe of interior compositions. White dwarfs in wide, non-interacting binary systems have a companion which interacts with the WD planetary regime and affects pollution in unknown but non-negligible ways. High-contrast, extreme AO imaging is a vital tool for study of non-interacting WDMS systems. We are conducting the ExAO Pup Search, an extreme AO survey of new and previously-known WDMS systems to probe the influence of the companion on WD pollution and planetary systems. The goals of the Pup Search are to detect new WDMS systems, probe for pollution in WDMS systems, and monitor WDMS orbital parameters.

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