RESEARCH PROPOSAL:

The ExAO Pup Search: Probing planets in wide binaries by leveraging the power of extreme adaptive optics towards White Dwarf + Main Sequence star systems

OBJECTIVE: **The study of the pollution and orbital characteristics of non-interacting white dwarf/main sequence star systems provides a direct probe of the influence of the wide companion on the planetary region.**

MOTIVATION: Multiple star systems are an extremely common outcome of the star formation process, especially for higher-mass stars [14]. I am interested in the formation and dynamical evolution of planetary systems around one star in a wide binary — “S-type", as opposed to “P-type" (circumbinary) planets — under the gravitational influence of the wide stellar companion as opposed to a single star. It is becoming clear that S-type planets are not uncommon [8, 5, 6], and companions will exert gravitational influence on the planetary regime throughout the star’s lifetime impacting the formation and survival of S-type planets. **Observational tests are critical for theoretical predictions of how and to what degree companions influence planetary systems throughout the star’s lifetime.**

White dwarfs (WD) with (non-interacting) main sequence star companions (WDMS) are an excellent laboratory for probing the influence of a wide companion at late stages of planetary system evolution. Due to their extreme gravity, elements stratify on short timescales (minutes - years) leaving pure H and He photospheres. Any metals observed in the spectra of WDs — called pollution — were deposited recently from the planetary regime [29]. WD pollution is the only method of probing the refractory compositions of exoplanetary material [e.g. 31, 26, 33, 23]. WDs show pollution independent of cooling age [27], requiring a mechanism(s) to deposit material that is independent of age [22]. A wide companion is one such possible mechanism [e.g. 32, 22]. **The role of the companion in driving material onto the WD is unknown**, but may impact the planetary regime through: 1. pushing previously stable planet orbits into regions of chaotic orbits as the primary loses mass and the companion’s orbit expands [32, 11], 2. evolving onto high-eccentricity orbits through external perturbations [4, 9, 28] inducing regions of chaos [2], 3. driving von-Zeipel-Kozai-Lidov oscillations [9, 15], 4. driving secular resonances [2], 5. pushing surviving planets onto close orbits [13], 6. inducing a 2nd or 3rd generation of planet formation [21].

Many of these scenarios produce observationally testable predictions. [25] determined the distribution of orbital parameters for a WD polluted by the Eccentric Kozai-Lidov (EKL) mechanism to which the orbital parameters of a population of polluted WDMS systems can be compared. Veras et al. [28, see Fig 3] made predictions of companion semi-major axis and eccentricity combinations for which the primary’s planetary regime is (un)stable at various stellar evolutionary phases which can be compared to (non-)polluted WDMS system architecture.

As one star evolves off the main sequence, they can either evolve into interacting or non-interacting [30] which expand as primary loses mass into a regime amenable to direct imaging instrumentation. Additionally, the number of known nearby white dwarfs is fewer than expected from stellar evolution [12, 10]. For so-called ‘Sirius-Like Systems" (SLS) — a multiple system containing a white dwarf with a more-luminous K-type or earlier companion(s) — the white dwarf contribution to the SED is drowned out by the more luminous MS star, and can’t be easily detected. **This motivates probing this population via high-contrast imaging detection methods**.

I propose an observational survey to leverage the power of the new extreme adaptive optics (ExAO) instruments MagAO-X and SCExAO towards detection and characterization of SLS

with a survey called TheExAO Pup Search: The extreme AO non-interacting white dwarf-main sequence binary system survey[1]. 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 systems with imaging and radial velocity 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 pollution, such as those in Stephan et al. 25 and Veras et al. 28 Fig 3.
3. Determine pollution rates for WDMS systems with VIS-X and HST and compare to single WDs and as a function of cooling age, and compare to estimates such as Veras et al. [29]

There is a demonstrated need in both exoplanet and WD communities for a dataset of this kind. We will grow the sample size of non-interacting white dwarf-main sequence binaries and produce observational tests of the role of wide companions on the planetary regime; as a byproduct we will also be contributing to the missing WD problem by identifying new WDMS systems in the local region and testing the wide companion influence on pollution. **We already observed 5 Pup Search systems with MagAO-X in 2022 and detected two new WD companions (Figure XX), which demonstrates the effectiveness of this survey design.**. Zuckerman [32] compiled 38 polluted WDMS and found that the companion suppresses the formation and/or long term stability of planets; they acknowledge that these are small-number statistics and call for further observational surveys with this goal in mind. It is possible that polluted WDMS may be rare, however a larger population size is required, which this survey will provide. It will also be challenging to detect pollution lines with VIS-X as lines are typically rare and weak; UV spectra with HST is optimal for line detection. The smaller mirror is not a challenge to spatial resolution moving to UV wavelengths as for both HST at 0.3μm and MagAO-X at 0.8μm, 1λ/D $\approx$ 25 mas, so new systems detected by MagAO-X should be accessible to HST in UV. Additionally, orbital periods for SLS can be long making orbital parameter determination difficult. Non-interacting orbital periods from 3–300,000 years are common Willems and Kolb [30]. My new SLS search is targeting objects close to the inner working angle of nearby stars, where periods are shorter and radial velocity will yield better orbit constraints. Astrometric and RV measurements made during this fellowship will contribute to long-term orbit monitoring of these systems for future orbit constraints beyond the fellowship period.

Suitability of Host Institution. MagAO-X, via Steward Observatory at University of Arizona (UA), is especially well suited to this science case (Objective 1 and 2). MagAO-X is built for extreme high contrast imaging on the order of 10^{-7}; contrasts involved in SLS [$\mathcal{O}(10^{-2} - 10^{-4})$] are easily achieved in short observation times. MagAO-X is optimized for optical wavelengths where WDMS star contrasts are much lower and inner working angles are smaller. MagAO-X achieves exceedingly high Strehl ratio ($\mathcal{O}$ 70% in z$'$) in optical wavelengths compared to other adaptive optics instruments. We also plan to use its high-resolution spectrograph, VIS-X, for spatially resolved spectra. While optical pollution features in white dwarfs are less common and harder to detect than UV, VIS-X will complement our planned UV HST spectra (Objective 3). SCExAO/VAMPIRES is also well suited to Objective 1 and 2. In addition to the ExAO benefits listed above, the newly-available 4-color imaging mode is invaluable for quickly characterizing new systems with minimal observational overhead. Observing with both MagAO-X and SCExAO opens up the survey area to both northern and southern targets. Additionally, Objective 2 can be supplemented with other Steward Observatory telescopes/instruments such as MMT/MAPS

[1]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 [3], first observed by Alvin Graham Clark [7], and confirmed as the second ever known WD via its spectrum obtained by Walter Adams [1]. Since Sirius A is the "Dog Star", Sirius B was nicknamed "The Pup"

and LBT/SHARK-NIR; Steward also allows ready access to radial velocity instrument such as NEID for orbit monitoring. The joint appointment of Olivier Guyon between Steward Observatory and NAOJ as SCExAO PI makes UA the ideal location to carry out this program.

Applicant Qualification. As a member of the MagAO-X team during my PhD I have had 24 hours MagAO-X observing time as PI awarded over 2 semesters, 18 of which were for preliminary Pup Search observations. The remaining 6 hours resulted in publication of a new binary system HIP 67506 AC [20]. I have extensive experience with long-period orbit monitoring [16, 17, 18]. I also have extensive experience with high-contrast image processing and data analysis [19, 20].

Will reviewers think this is not really a planets proposal?

TIMELINE

Figure 1 displays a Gantt chart for the organization of this project. In year one my focus will be on detecting previously unknown WDMS systems with MagAO-X and SCExAO (Objective 1). As this process has already begun during my PhD, I already have a robust target list of MS stars highly likely to contain a hidden WD as selected by UV excess in Ren et al. [24], from which I have discovered at least one new WDMS (Figure 2). I will also compile a target list for orbit monitoring of known SLS and begin observations with other Steward telescope resources (Objective 2). I expect publication of new WDMS detections at the end of year one. In year two I will continue Objective 1 and 2 observations and begin to shift focus to Objective 3 by applying for HST and VIS-X time, with a second publication of new detections and preliminary orbit monitoring results expected near the end of year two. In year three my focus will primarily be on HST and VIS-X spectroscopic observations, with publication of (un)polluted WDs and pollution rates expected near the end of year three.

RISK MITIGATION

This ambitious survey relies on the availability of primarily two ground-based instruments, MagAO-X and SCExAO, which are subject to observing and maintenance schedules, travel restrictions, and weather. MagAO-X's observing schedule was significantly impacted by COVID and related travel restrictions, and our 2022A observing run was hampered by weather, both of which would impact Objective 1. Objective 2 can be supplemented with other Steward Observatory resources, and Objective 3 is not impacted by ground-based restrictions. Objective 3 relies on the availability of HST UV spectroscopy, with the main risk being continued availability of HST and being awarded observing hours for this program.

OUTCOMES

Short term outcomes of the fellowship include providing the **exoplanet community** with a robust investigation of S-type planets in binaries at the end of the star's lifetime, with new WD pollution data providing more evidence of refractory compositions of exoplanets, and providing the **white dwarf community** with an expanded population of SLS. These data produced by this fellowship will be invaluable to both fields. This program builds upon all the strengths developed during my PhD while also pushing me into the new regimes of UV spectroscopy and space-based observations. It enables me to build new professional relationships within the exoplanet community as well as forge new collaborations in the polluted white dwarf community.

As the timescale of some aspects of this program is long, it will not be fully completed during the 3 years of this fellowship. **Funding of the program will set me up for a career-long investigation of polluted white dwarfs in non-interacting binaries. I intend to pursue an active research career beyond this fellowship, and the experience of this fellowship will be vital for forging an impactful career.**

Figure 1: Project Gantt Chart

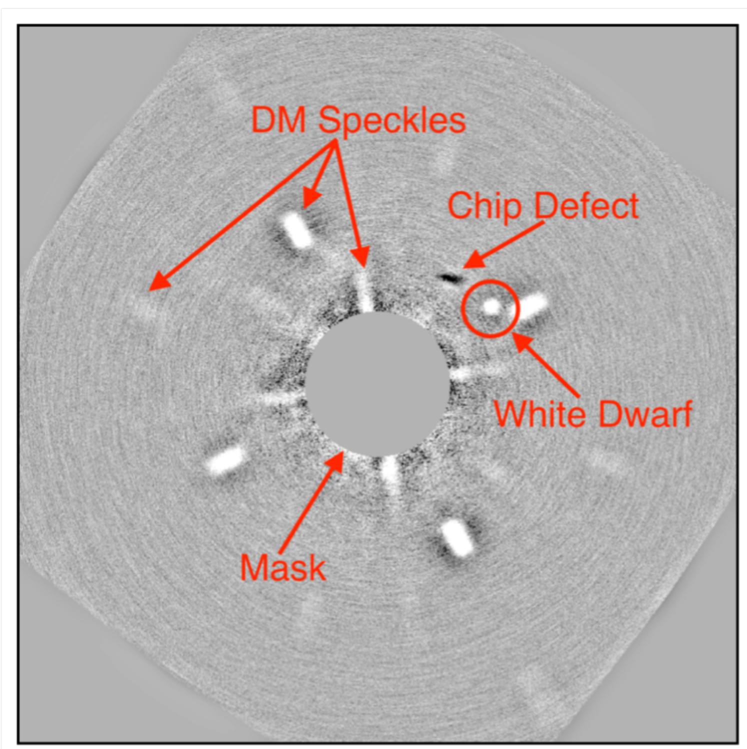

Figure 2: A new WD companion (red circle) to a main sequence star discovered in i' band with MagAO-X in 2022 as part of the Pup Search program. Host star PSF was removed by unsharp mask and radial profile subtraction; mask, chip defect, and speckles caused by the deformable mirror are labeled. The new WD companion is indicated by the red circle.

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