1. OVERVIEW

Studies of extrasolar planets and their environments hold promises for answering the ultimate questions since the beginning of humankind: are we alone in this Universe? How does our home, the Earth, originate and evolve? Are there other habitable planets? As a Ph.D. candidate at UCLA, I am actively involved in this intriguing research field. In particular, using multi-wavelength observations carried out both on the ground and in space, I study externally polluted white dwarfs, which offer a unique and powerful approach to measure the elemental compositions of extrasolar planetesimals, the building blocks of planets.

The atmospheres of cool white dwarfs (effective temperature $T_* < 20{,}000$ K) typically show a high degree of purity, dominated by either hydrogen or helium. Based on *Keck* observations, it is found that at least a quarter of these fossil stars show absorption lines from elements heavier than helium, typically the Ca II-K line [22,24]. These materials must be supplied from an external source, considering the diffusion timescales of heavy elements are orders of magnitude less than a white dwarf's cooling age [14]. Meanwhile, infrared observations show that 1-3% of single white dwarfs have a dust disk, which are also among the most heavily polluted [6]. The currently widely-accepted model predicts that some ancient planetesimals can survive into the white dwarf phase and get perturbed into the tidal radius of the central star, feeding onto the white dwarfs' atmosphere [3,9]. Via this mechanism, extrasolar planetesimals leave two observable imprints on the white dwarf, i.e. an infrared excess arising from an orbiting dust disk and various degrees of atmospheric pollution [12].

According to recent *Spitzer* observations, at least 4% of white dwarfs have an infrared excess from breakups of extrasolar planetesimals [1]. Our spectroscopic studies using the *Keck* and the *Hubble Space Telescope* (HST) have revealed 19 heavy elements in the atmosphere of polluted white dwarfs, including C, S, O, Na, Cu, Mn, P, Cr, Si, Mg, Fe, Co, Ni, V, Sr, Ca, Ti, Al and Sc [23, 21, 10]. The accreted mass is comparable to that of an asteroid in our own solar system, and the most sensitive mass fraction limit is $\sim$5 ppm, for Sc in WD J0738+1835 [5]. To zeroth order, we find that the compositions of extrasolar planetesimals are strikingly similar to solar system objects; Earth serves as a good fiducial for their abundance pattern: (i) oxygen, magnesium, silicon and iron are always dominant and their sum is more than 85% of the total mass [13]; (ii) volatile elements, especially carbon, are typically depleted by more than a factor of 10 compared to solar abundances[1] [11,8].

2. PROPOSED PROGRAM

With the joint capabilities of *Spitzer*, *Keck* and *HST*, I propose to extend our previous studies to all known dusty white dwarfs and address two key questions:

- What is the frequency of extrasolar planetesimals that end up as a dust disk around white dwarfs?
- What are the elemental compositions of extrasolar planetesimals?

Q1: What is the frequency of extrasolar planetesimals that end up as a dust disk around white dwarfs?

At present, a total of 28 white dwarfs are known to harbor $\sim$ 1000 K disks[2] [6,20]. Their effective temperatures range between 9700 - 24,000 K. As illustrated in Figure 1, all dusty white dwarfs tend to be more heavily polluted, i.e. having a high accretion rate. I plan to use the *Spitzer*/IRAC to observe white dwarfs at different temperature regions to constrain the frequency of extrasolar planetesimals that end up as a dust disk around white dwarfs.

As shown in Figure 1, there are quite a few cool white dwarfs ($T_* < 9700$ K) with an accretion rate higher than 3×10^8 g s^{-1} but none of them have an infrared excess. So far, this remains a mystery. We were awarded *Spitzer* cycle 7 time to look for infrared excess around 10 heavily polluted cool white dwarfs. The results are reported in [20], and one explanation therein for the lack of dust is that these cool stars are accreting comet-like objects, which are compositionally different than the planetesimals accreted onto the warm stars and are too fragile to form a dust disk. We also have an approved Spitzer cycle 9 program to follow up 5 extremely polluted cool white dwarfs newly identified from the SDSS [15]. All of them have an accretion rate higher than 3×10^8 g s^{-1} and this will more than double the number of extremely polluted white dwarfs observed in this temperature region.

At the warm end, no systematic infrared observations have been conducted; optical searches of atmospheric pollution are ineffective because the best studied Ca II K-line becomes quite weak. However, the disk fraction is expected to be at least equal to, if not higher than, 4% derived for cooler stars [1]. Dynamical models suggest that tidal disruption events of extrasolar planetesimals peak around 30 Myr ($T_* \sim 24{,}000$ K) [4]. In the standard geometrically thin, optically thick disk model, dust can survive around white dwarfs with temperatures up to 30,000 K [9]. We were awarded 28.4 hours of *Spitzer* cycle 8 time to observe 39 white dwarfs between 20,000 K and 30,000 K. By constraining the disk frequency of white dwarfs in different temperature regions, we will have a better understanding about the evolution of planetary systems around white dwarfs.

Q2: What are the elemental compositions of extrasolar planetesimals?

It has been demonstrated that combining high-resolution optical *Keck*/HIRES and ultraviolet *HST*/COS observations is essential to determining the whole-body compositions of extrasolar planetesimals and contrasting with solar system objects [10]. For example, we compared the composition of the parent body accreted on GD 362 with that of meteorites and found the best solar system analog is mesosiderite, as shown in Figure 2. I propose to spectroscopically follow up all the currently-known dusty white dwarfs, which are also the most heavily polluted ones, to compile an atlas of compositions of extrasolar planetesimals.

Depending on the stellar temperature, optical observations are typically sensitive to the major rock-forming elements, such as iron, magnesium, silicon and calcium, while the ultraviolet is crucial to determining the abundances of oxygen as well as volatile elements, such as carbon and sulfur. As listed in Table 1, there are 18 targets that: (i) have V band magnitude brighter than 17.5; (ii) are accessible with *Keck* and/or *HST*. Most ground based observations have been completed and the data are currently being analyzed. We were awarded *HST* cycle 18 time to observe 4 of these stars and we will continue to propose to use the *HST* to observe the remaining targets.

From our past experience, by comparing the data with white dwarf atmosphere models computed by D. Koester, we typically can determine the element-to-element abundance ratios to better than 0.2 dex. To derive the original abundance of the parent body, additional modeling is required [11,7]. Fortunately, most dusty white dwarfs, especially if they are dominated by hydrogen, are likely to be in a steady state, where the rate of accretion onto the atmosphere is balanced by the rate of settling out of the lower boundary [14].

After determining the original composition, we can perform exo-meteoritics analyses and study the formation as well as evolution of extrasolar planetary systems. We will utilize the rich meteorite database to look for solar system analogs [21]. We will look for extrasolar planetesimals with exotic compositions, such as carbon-dominated (C and SiC) and refractory-dominated (Ca and Al) as predicted in planet formation models [2]. We will also look for additional evidence of differentiation, collisions and other exo-geological processes given that we found most extrasolar planetesimals cannot be formed under nebular condensation alone, indicating a more violent history than solar system objects [21].

This multi-wavelength study by using the *Spitzer*, *Keck* and *HST* clearly fits into NASA strategic plan about exoplanet exploration, especially in the unknown territory of the internal compositions of extrasolar planetesimals. No other techniques is on the horizon that can achieve the same level of sensitivity. Most data have been acquired and I am well experienced in analyzing them to fulfill the proposed program in two years. By increasing the number of white dwarfs studied and the range of detectable elements, it will substantially deepen our understanding of extrasolar planetary systems. This program will also lay the groundwork for future discoveries with the next generation telescopes such as *TMT*, *GMT* and *JWST*.

NOTES AND REFERENCES

[1] There are a couple of white dwarfs with solar carbon-to-silicon ratio [16]. However, the source of this pollution is unclear and more analysis is forthcoming.
[2] Warm *Spitzer* is only capable of detecting $\sim$ 1000 K warm dust. So far, only two white dwarfs, PG 1225-079 and G166-58 are found to have $\sim$500 K cool dust but this type is excluded in the discussion here.

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Table 1: Target List

	Name	SpT	T_* (K)	V (mag)	HIRES	COS
WD 0106-328		DAZ	15,700	15.5	✓	✗
WD 0146+187	GD 16	DAZB	11,500	15.9	✓	✗
WD 0300-013	GD 40	DBAZ	15,300	15.6	[13]	[10]
WD 0307+077		DAZ	15,300	16.4	✓	-
WD 0408-041	GD 56	DAZ	14,800	15.5	✓	✗
WD 0843+516		DAZ	23,900	16.2	✓	[8]
WD 1015+161		DAZ	19,300	15.8	✓	[8]
WD 1041+092		DAZ	18,300	17.4	✓	✗
WD 1116+026	GD 133	DAZ	12,200	14.7	✓	✓
WD 1150-153		DAZ	11,700	15.9	✓	✗
WD 1226+110		DAZ	22,020	16.6	✓	[8]
WD 1457-086		DAZ	20,300	15.4	✓	✗
WD 1541+650		DAZ	11,900	15.7	✓	✗
WD 1729+371	GD 362	DAZB	10,500	16.2	[23]	[21]
WD 2115-560		DAZ	9,600	14.5	-	✗
WD 2221-165		DAZ	10,100	13.0	✓	-
WD 2326+049	G29-38	DAZ	11,700	13.0	✓	✓
	J2209+1223	DBZ	17,300	17.4	✗	-

Comments

(a) Meanings for different symbols: ✓: data have been obtained; ✗: no data obtained; -: not applicable with this specific telescope.

(b) There are 3 additional dusty white dwarfs that have been studied by other groups and they are not included in this list: WD J0738+517 [5], WD 1929+012 [17,18,19,8] and Ton 345 (D. Koester, private communication).

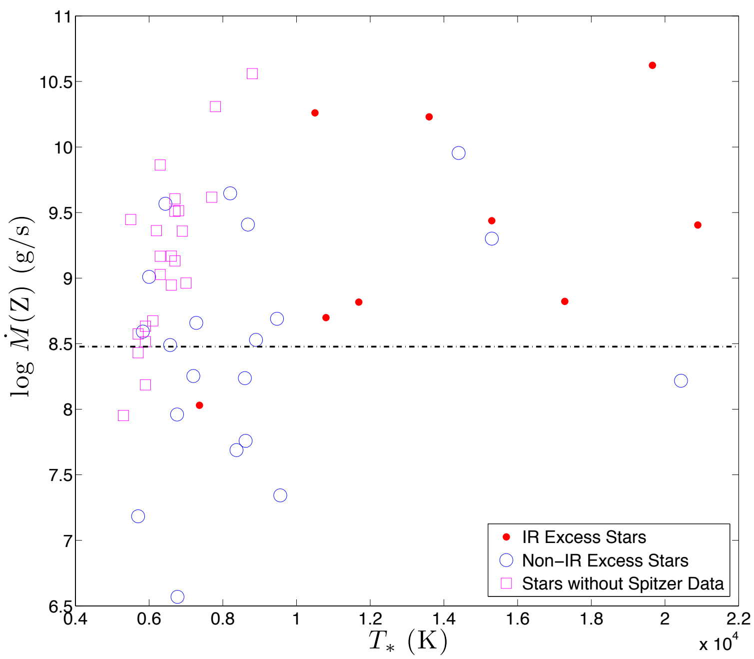

Fig. 1.— From [20], derived accretion rate of heavy elements versus white dwarf temperature. The dash-dotted line represents an accretion rate threshold of 3×10^8 g s^{-1} and over 50% of single white dwarfs with accretion rates at least this high display an infrared excess [6].

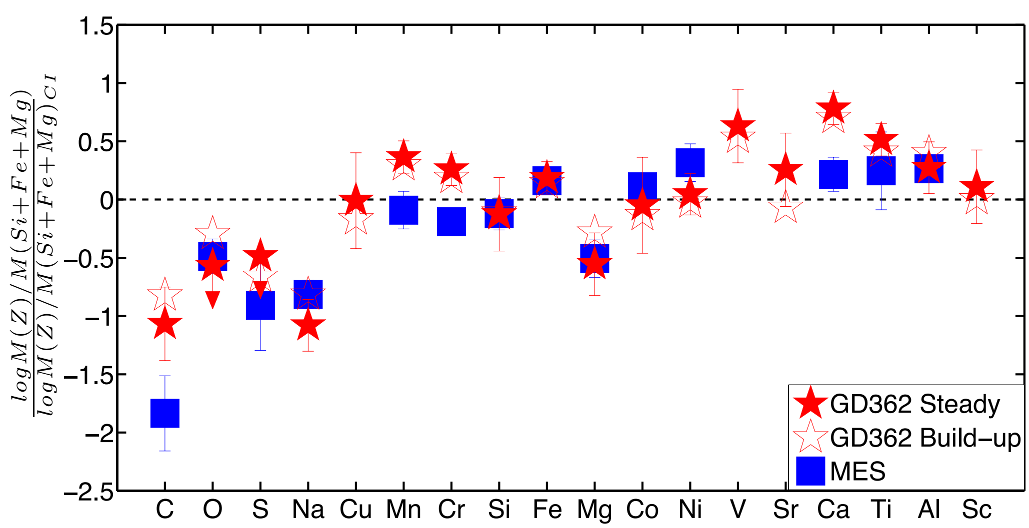

Fig. 2.— From [21], mass fraction of heavy elements compared to the summed mass of Si, Fe and Mg normalized to that of CI chondrites. Two models are plotted for GD 362, steady-state and build-up stage. The best solar system analog to the parent body accreted onto GD 362 is mesosiderite (MES). There is no reported whole rock abundance of Cu, V and Sr in MES.