OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Aug–Dec **Proposal type:** short-term

Elemental Abundances of Planetary Debris in the Atmospheres of Four White Dwarfs with Newly Discovered Dusty Disks

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Abstract of Scientific Justification

It is now well established that white dwarf stars are frequently polluted by asteroid-like planetesimals and provide powerful insight into the rocky planets they built as $1.2 - 3.0\,M_{\odot}$ stars, in the same way that meteoritic fragments of Solar System asteroids yield the bulk compositions of the terrestrial planets. Using *Spitzer*, we have recently identified four new circumstellar disks orbiting nearby white dwarfs – we now wish to obtain high-resolution optical spectroscopy of their metal-polluted atmospheres to indirectly determine detailed abundances of the planetary debris itself.

We propose MMT BChan echellette spectroscopy of these four stars to measure the abundances of Mg, Si, Fe, and other elements that will constrain the nature of the exoplanetary bodies currently being consumed. These chemical inventories will enable assessments of (exo)planet formation processes by examining the major end products; e.g. ratios such as Al/Fe can distinguish material that is crust or mantle-like vs. core-like parent bodies. The proposed study will determine abundances for all major rock-forming elements but oxygen (which requires ultraviolet spectroscopy with *HST*), and plays a critical role in the accounting of common metal oxides relative to total oxygen that can indicate H_2O in rocky planetesimals.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	MMT	f/9	BChan			2	dark			no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: We have identified a window from 9 Nov - 1 Dec during which all four stars can be observed for at least 2.0 hours on source above airmass 2. Grey or even dark time is preferred as a bright moon could adversely affect the wavelength regions of interest.

no text past this line

A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	WD 2132+096	21 34 50.77	+09 55 20.0	g=16.0
2	WD 2328+107	23 30 41.66	+11 02 06.2	g=16.0
3	WD 0246+734	02 51 51.24	+73 41 35.6	g=17.2
4	WD 1018+410	10 21 55.50	+40 50 13.9	g=16.2

Approval for Instrument Use from PI: _____

*(have instrument PI signature appear on, or attach PI e-mail to, **all** copies)*

Graduate students *(provide the following information for **each** student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on **all** submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

Background:
We now stand firmly in the era of small exoplanet detection via *Kepler* and other state of the art facilities. Yet the empirical characterization of these most intriguing planets is extremely challenging. Transit plus radial velocity information can yield planet mass and radius, and hence planet density, but the bulk composition remains degenerate and model-dependent. The abundances of a handful of giant exoplanet atmospheres can be estimated from transit spectroscopy, but probe only their most tenuous outer layers. Fortunately, as discussed below, polluted white dwarf stars can yield highly accurate information on the chemical structure for rocky minor planets (i.e. exo-asteroids), the building blocks of solid exoplanets.

A decade of observational and theoretical investigations by many astronomers have shown that, over a wide range of stellar $T_{\rm eff}$, the presence of heavy elements in white dwarf atmospheres is evidence for orbiting planetary systems. Each exoplanetary system must contain at least one rocky debris belt and one major planet (Veras et al. 2013, MNRAS, 431, 1686; Mustill & Villaver 2014, MNRAS, 437, 1404). The gravitational field of the planet(s) can perturb planetesimals into highly eccentric orbits, so that they pass near the white dwarf and are tidally disrupted. *Spitzer* and complementary ground-based observations have established a firm connection between the atmospheric heavy elements in white dwarfs and the presence of dust within the tidal radius of the star (von Hippel et al. 2007, ApJ, 662, 544; Farihi et al. 2009, ApJ, 694, 805).

The circumstellar material gradually falls onto the star and can be directly observed in the photosphere to reveal the elemental composition of parent bodies – these may be asteroids or rocky planets or portions thereof. For the most heavily polluted stars, detailed compositional models of the (differentiated) parent bodies can be constructed (Zuckerman et al. 2007, ApJ 671, 872; Klein et al. 2010, ApJ 709, 950; Gänsicke et al. 2012, MNRAS, 424, 333). Between optical and ultraviolet spectra (with COS on *HST*), in total about 20 heavy elements have been detected in one or more polluted white dwarfs.

The link to exoplanets themselves can be understood in the following way. The minimum masses necessary to cause the atmospheric pollution phenomenon in white dwarfs (not to mention the circumstellar disks) correspond to planetesimals with diameters of tens to a few hundred km (Farihi et al. 2010, MNRAS, 404, 2123). Because planet formation is a runaway process of growth after the meter barrier, these large planetesimals in white dwarf systems are signposts for rocky planet construction.

Furthermore, major planets are required to perturb asteroids into star-crossing orbits (Debes et al. 2012, ApJ, 747, 148; Frewen & Hansen 2014, MNRAS, 439, 2442), and therefore we expect that complex planetary systems still orbit these remnants. This dynamic channel also exists in the Solar System, where Jupiter perturbs Main belt asteroids towards the inner system, providing a likely source of water and volatiles to the terrestrial planets (Morbidelli et al. 2000, M&PS, 35, 1309). Furthermore, the discovery of water in the rocky debris polluting the white dwarf GD 61 is consistent with an extrasolar asteroid belt straddling the snow line, as in the Solar System (Farihi et al. 2013, Science, 342, 218).

The exoplanetary systems orbiting the A-type stars HR 8799, Vega, and Fomalhaut appear to share this basic architecture (Su et al. 2009, ApJ, 705, 314; Su et al. 2013, ApJ, 763, 118), with asteroid belt analogs located near (and interior to) their respective snow lines, and with (confirmed or inferred) giant planets just exterior. Initial simulations demonstrate that the exoplanet HR 8799e will perturb main belt analogs towards the inner system (Contro et al. 2015, PASA, in press [arXiv:1502.02315]), providing a possible source of water to any terrestrial planets. Thus, it appears that the progenitors of polluted white dwarf systems may be relatively common and similar to the Solar System; *we can probe the compositions of their exo-terrestrial minor planets via their polluted white dwarf descendants.*

By studying these evolved planetary systems, we gain empirical insight into the assembly and chemistry of terrestrial exoplanets that is unavailable for any exoplanet orbiting a main-sequence star. In the Solar System, the asteroids (or minor planets) are leftover building blocks of the terrestrial planets, and we obtain their compositions and hence that of the terrestrial planets by studying meteorites. Similarly, one can infer the composition of terrestrial exoplanets by studying the chemistry of their tidally destroyed and accreted asteroids at polluted white dwarfs.

Proposed Observations:
Our team has recently identified four new circumstellar disks orbiting white dwarfs with Spitzer IRAC (Figures; Bergfors et al. 2014, MNRAS, 444, 2147; Rocchetto et al. 2015, MNRAS, 449, 574). All four systems exhibit clear infrared excess emission at 3.6 and 4.5 microns, indicating the presence of closely-orbiting planetary solids. We propose BChan echellette observations to indirectly obtain the bulk chemical composition of the circumstellar debris – via the polluted stellar atmospheres – and hence the disrupted parent bodies.

In these systems with infrared excess, we can confidently infer the ongoing accretion of debris (Rafikov 2011, MNRAS, 732, L3), and use a steady-state analysis to link the atmospheric metal abundances with those of the planetary material. These opportunities are rare, as only a fraction of all polluted white dwarfs exhibit infrared excess, and reveal a clear accretion history that obviates the need for any assumptions in the material abundance analysis (e.g. Zuckerman et al. 2011, ApJ, 739, 101). Critically, these systems represent a unique opportunity for *JWST* where both 1) detailed mineralogy of the debris can be measured in situ with infrared spectroscopy (e.g. MIRI) and 2) the bulk, element to element ratios of the material can be obtained via spectroscopy of the debris-polluted atmosphere. We now propose to obtain the latter datasets for these newly identified dusty white dwarf systems, and thus pave the way for ground-breaking *JWST* observations in the near future.

Two targets are known to be polluted, with only Ca detected in previous, modest quality data (0246+734, 2132+096), while two others were identified in a blind *Spitzer* IRAC search of relatively warm ($17\,000 - 25\,000$ K), nearby, bright white dwarfs (1018+410, 2328+107). Notably, we expect these latter two white dwarfs to be highly polluted, as studies indicate that in this range of $T_{\rm eff}$, only those stars with the highest metal abundances and accretion rates exhibit infrared excesses (Farihi et al. 2009, ApJ, 694, 805; Gänsicke et al. 2012, MNRAS, 424, 333).

Our observational goals are to detect multiple transitions of the major elements involved in terrestrial planet formation: primarily Mg, Si, Fe, Ca, Al, and secondary trace elements such as Ti, Cr, Ni. [N.B. Despite it's importance, we cannot simultaneously detect oxygen and the other major rock-forming elements, as ultraviolet observations are typically required. However, the critical role of oxygen in rocky planet formation, and especially as a indicator of H_2O in at least one system (Farihi et al. 2013, Science, 342, 218), demands its presence be studied separately, and hence we will propose *HST* / COS observations of these stars].

The atmospheric metal abundances will be measured by fitting white dwarf atmospheric models to the data, and the debris compositions will be derived analytically by exploiting the steady-state balance between ongoing accretion and diffusion. The planetary chemistry will be compared to Solar System materials and planet formation models (e.g. Bond et al. 2010, ApJ, 715, 1050). The team has extensive experience and a solid track record in this area.

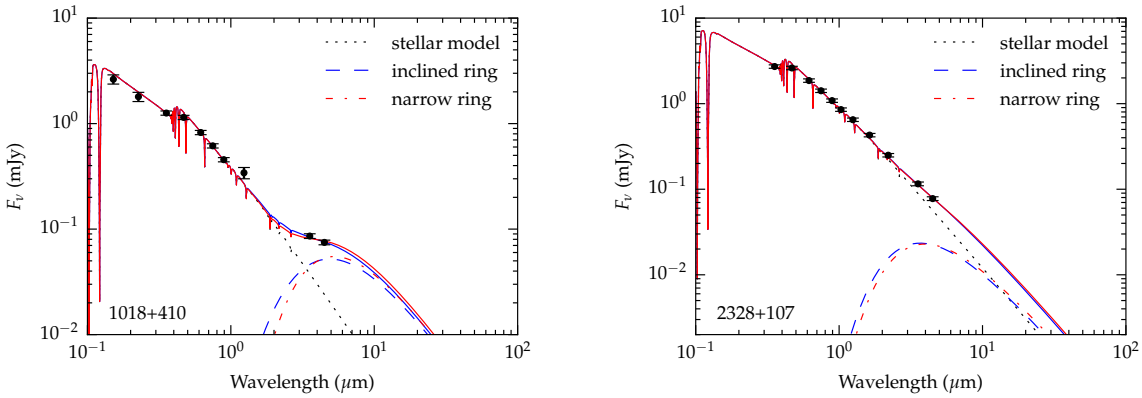

Figure 1: Examples of new dusty white dwarfs. Spectral energy distributions are shown for two $T_{\rm eff} \approx 20\,000$ K stars recently found to have $> 3\sigma$ excesses in both 3.6 and 4.5 μm Spitzer IRAC photometry (Rocchetto et al. 2015). The disks range from prominent to subtle, underscoring the need for *Spitzer* in their discovery and characterization. These two white dwarfs have never been examined with sufficient spectral resolution to detect and study atmospheric heavy elements arising from the infalling planetary debris.

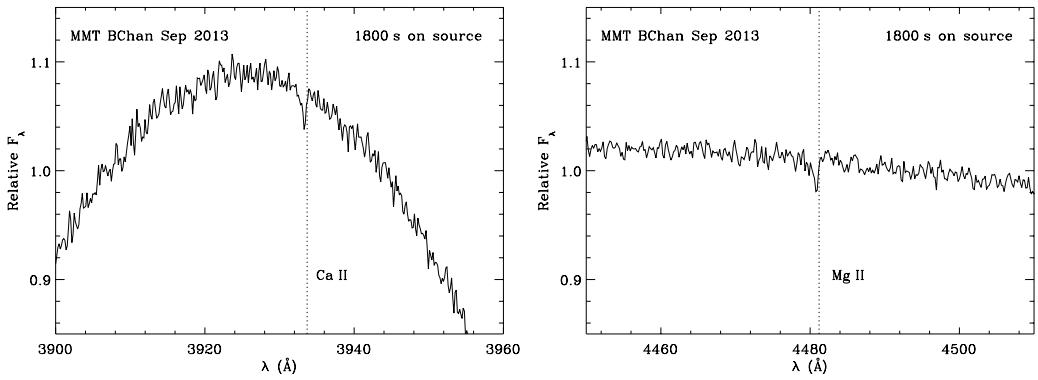

Figure 2: MMT BChan echellette ($R \approx 10\,000$) observations reveal weak lines of Ca II and Mg II in the spectrum of the dusty white dwarf WD 2329+407 (Hoard et al. 2015, in preparation). *These data were obtained under average conditions and with a total on-source time of only 30 minutes.* Our proposed observations of similar targets will go substantially deeper to reveal additional elements and multiple transitions, with equivalent widths as small as 50 mÅ. In order to achieve these observational goals, we require S/N > 100 and moderately high-resolution spectra.

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

The observational goal is to measure abundances for a few to several heavy elements, as well as for H, at equivalent widths as small as 50 mÅ. Therefore, we require spectroscopy with resolving power of $R \gtrsim 10,000$ and S/N $\gtrsim 100$ over relevant regions where features are expected. Ca II K lines are already known to be present in two targets, and we will detect other metals which are almost certain to be present (Mg, Si, Fe), and additional heavy elements which are often seen in highly polluted white dwarfs (e.g. Al, Cr, Ti; Zuckerman et al. 2007, ApJ 671, 872; Klein et al. 2010, ApJ 709, 950). The greater the number of detected absorption lines, the better will be our abundance determinations. Elemental abundances, relative to H or He, will be calculated in the standard fashion: the observed spectra are compared to a grid of white dwarf model atmospheres where the composition varies until good agreement is achieved between the two (Koester 2009, A&A, 498, 517).

We must target the ultraviolet-blue region ideal for the highest number of metal lines (and species), and the yellow-red region is necessary for Hα, Na, and a few key Si lines. Therefore, we require a large collecting area and an instrument with moderately high resolution, ultraviolet-blue sensitivity and wide wavelength coverage. To meet these goals, we propose to use the MMT BChan spectrograph with the echellette grating, covering 3200 to 7200Å in an efficient, single setting. *We are experienced with this instrument mode – one of us re-commissioned this observing mode between 2011 and 2013; some of our data is shown in Figure 2.*

Our experience with the echellette has shown that we need $6 - 8$ exposures of 30 min each to obtain S/N > 100 for targets of $16^{\rm th}$ magnitude. While the echellette covers a wide wavelength range, it is about a factor of two 'slower' than other BChan gratings, and it is important to reset the parallactic angle often during these deep observations, to minimize slit losses across the wide wavelength range of the echellette. In this way, we can get deep spectra for two stars per night, and thus request 2 nights for our four targets.

[In actuality, due to the wide R.A. range of the targets, we will observe each target for around 2.0 hours each night, for a total of 3-4 hours per target over the 2 requested nights].

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

We expect to complete this project with the 2 requested nights in 2015B.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). (**up to one page**)*

This is a new project and collaboration.