The bulk composition of exo-planets

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Motivation

Priorities in exo-planet research are rapidly moving from finding planets to characterizing their physical properties. Of key importance is their chemical composition, which feeds back into our understanding of planet formation. Mass and radius measurements of transiting planets yield bulk densities, from which interior structures and compositions can be deduced (Valencia et al. 2010). However, those results are model-dependent and subject to degeneracies (Rogers & Seager 2010; Dorn et al. 2015). Transmission spectroscopy can provide insight into the atmospheric compositions (Sing et al. 2013; Deming et al. 2013), though cloud decks detected in a number of super earths systematically limit the use of this method (Kreidberg et al. 2014). *For the foreseeable future, far-ultraviolet spectroscopy of white dwarfs accreting planetary debris remains the only way to directly and accurately measure the bulk abundances of exo-planetary bodies. The exploitation of this method is limited by the sensitivity of HST, and significant progress will require a large-aperture space telescope with a high-throughput ultraviolet spectrograph.*
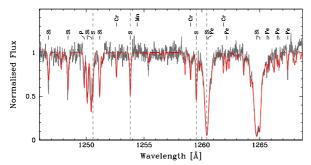
Evolved planetary systems

Practically all known planet host stars, including the Sun, will evolve into white dwarfs, and many of their planets will survive (Veras et al. 2013; Villaver et al. 2014). Observational evidence for such evolved planetary systems includes the detection of trace metals in the white dwarf photospheres (Koester et al. 1997), and infrared and optical emission from circumstellar debris disks (Zuckerman & Becklin 1987; Gänsicke et al. 2006; Farihi et al. 2009). The generally accepted model explaining these observation is the tidal disruption of asteroids, minor planets, or planets (Jura 2003; Debes et al. 2012; Veras et al. 2014) perturbed onto star-crossing orbits by dynamical interactions with planets (Debes & Sigurdsson 2002; Frewen & Hansen 2014; Veras & Gänsicke 2015). Spectroscopic surveys now unambiguously demonstrate that 25-50% of white dwarfs host evolved planetary systems (Zuckerman et al. 2003, 2010; Koester et al. 2014).

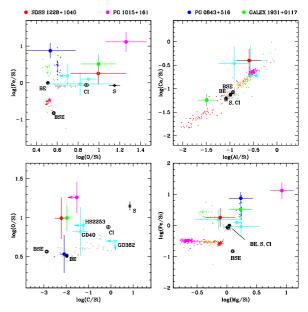## Debris-polluted white dwarfs as tracers of exo-planet bulk abundances

In a pioneering paper, Zuckerman et al. (2007) showed that measuring the photospheric abundances of debris-polluted white dwarfs provides an unrivaled window into the bulk composition of exo-planetary material for planetary bodies with masses of $10^{20} - 10^{25}$ g (Girven et al. 2012), i.e. ranging from several 10 km-sized asteroids to nearly the mass of Pluto.

The ultraviolet wavelength range is fundamental for this work, as it contains strong transitions of the rock-forming elements (Si, Fe, Mg, O), refractory litophiles (Ca, Al, Ti), and in particular of volatile elements (C, N, P, S) that trace the formation region of the planetary material relative to the snow line. We have led ten *HST*/COS programs that demonstrated the diagnostic potential of extra-solar cosmochemistry using white dwarfs, corroborating the rocky, volatile-depleted nature of the planetesimals (Jura et al. 2012; Xu et al. 2013), and detecting a variety in bulk compositions similar to, if not exceeding, that seen among solar-system bodies (Gänsicke et al. 2012, see Fig. 1). Noticeably, we have discovered water-rich planetesimals (Farihi et al. 2013), which provide the potential for delivering water to planets in the habitable zone.

The measured planetary debris abundances provide important input into our understanding of planet formation. Of particular importance for the properties of planetary systems are the C/O and Mg/Si ratios. C/O ratios > 0.8 would result in a radically different setup from the solar system, with O-chemistry replaced by C-chemistry, which is discussed abundantly in the literature (e.g. Moriarty et al. 2014). The Mg/Si ratio determines the exact composition of silicates, which in turn has implications for planetary processes such as plate tectonics. Furthermore, the relative abundances of Fe and siderophiles (Cr, Mn, S, Ni), and of refractory litophiles (Al, Ca, Ti) provides insight into the core and crust formation, respectively (Jura &

Figure 1. Planetary debris is detected in far-ultraviolet spectroscopy of white dwarfs (top), providing bulk-abundances for exo-planetary bodies with masses of $\simeq 10^{20} - 10^{25}$ g. About 15 systems studied so far are all "rocky", but show a large variety in their detailed compositions (right: large dots with error bars are extra-solar planetesimals, small dots are solar system meteorites).

Young 2014; Melis et al. 2011; Dufour et al. 2012). In contrast to indirect measurements, such as abundance studies of planet host stars (e.g. Delgado Mena et al. 2010), far-ultraviolet spectroscopy of debris-polluted white dwarfs provides a *direct measure* of those ratios. The results from our published studies of have already informed recent models of planet formation (Carter-Bond et al. 2012).

However, global insight into the chemistry of planetary systems will only be possible from the detailed photospheric abundance studies of a substantial number of white dwarfs. The current roster of planetary debris abundance studies with at least five detected elements stands at $\simeq 15$ (Jura & Young 2014). With *HST*, we may double, maybe triple this number over the next couple of years, but beyond that, the aperture of Hubble is too small to make significant progress.

Road-map for the next two decades, and the need for a large UV mission

Over the next four years, *Gaia* will identify $\simeq 200\,000$ white dwarfs brighter than 20th magnitude. This sample will be volume-limited out to 300pc for white dwarfs with cooling ages of up to 600Myr, i.e. sufficiently hot to have significant ultraviolet flux. Ground-based spectroscopic follow-up of this sample (DESI/WEAVE/4MOST) will identify 1000s of strongly polluted white dwarfs, but typically only provide abundances for Ca and/or Mg. In addition, cross-correlation of the *Gaia* white dwarfs with the *EUCLID* and *WFIRST* surveys will result in the detection of 100s, possibly 1000s of debris discs. The detection of circumstellar debris is a direct proxy for metal-pollution at ultraviolet wavelengths. A subset of these debris discs will be bright enough to be followed-up with *JWST*/MIRI, providing detailed mineralogy. Those systems are particularly valuable, as the dust mineralogy can be directly compared to atomic abundances obtained from far-ultraviolet spectroscopy of the debris-polluted white dwarfs.

In other words, the known sample of evolved planetary systems will explode, similar to the dramatic increase in the number of planets around main-sequence stars we witness thanks to missions like *Kepler*, *TESS*, and *PLATO*. To fully exploit the potential of evolved planetary systems for a detailed, large-scale statistical study of the bulk abundances of exo-planetary systems requires a large-aperture ultraviolet mission that can provide follow-up spectroscopy for several hundred debris-polluted white dwarfs.

Instrumental requirements

Assuming a factor 30 increase in sensitivity compared to COS ($\times 15$ for a 10 m aperture, and $\times 2$ from improved optics, and improved orbital visibility) will increase the available volume for detailed abundance studies by a factor $\simeq 150$ compared to what can be reached with *HST*, sufficient to include > 1000 potential targets for high-quality ultraviolet spectroscopic follow-up.

- Spectral resolution. A resolution of at least 20 000, better 50 000 is necessary to resolve photospheric and interstellar features, and to avoid blending of lines.

- Spectral range. The "traditional" far-ultraviolet range 1100 to 1800 Å contains most of the relevant atomic transitions. Extending coverage to 950 Å, i.e. including Lyβ and Lyγ, would be greatly improve the atmospheric parameters, T_{eff} and $\log g$, which, in turn, result in more accurate diffusion velocities, and finally abundances. The shorter-wavelength range also contains a number of higher-ionization lines detected in hotter, younger white dwarfs.

- Signal-to-noise ratio. The abundance measurements require a minimum S/N of 40 to model the strongest absorption lines. Detection of trace species not observed so far (e.g. N, rare earth elements) will need higher S/N, of up to 100, which is currently difficult to obtain with COS because of the limited telescope aperture, and fixed-noise patterns in the detectors.

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