

# Planetary Systems Around White Dwarfs

Boris Gänsicke, [boris.gaensicke@warwick.ac.uk](mailto:boris.gaensicke@warwick.ac.uk)

The vast majority of all known planet-hosting stars, including the Sun, will eventually evolve into red giants, lose a significant fraction of their mass as a planetary nebula, and finally end their lives as white dwarfs: extremely dense Earth-sized stellar embers that slowly consume their thermal heat content, monotonously cooling for billions of years. Only close-in planets will be devoured during the red-giant phase, whereas all surviving planetary bodies will see their orbits widening due to the mass loss of the host star.

In the solar system, Mars, the asteroid belt, and all the giant planets will escape evaporation, and move out by about a factor of two. Given the ubiquity of planets around main-sequence stars, it is certain that many of the known white dwarfs were once hosting planets, and it is very likely that a fair fraction of them still have remnants of their planetary systems. These systems offer a glimpse into the future of the solar system, and provide insight into the bulk composition of exo-planetesimals, as well as the frequency of rocky planetary systems around A-type stars.

## Signposts of evolved planetary systems

The strong surface gravity of white dwarfs ( $\sim 40,000$  stronger than that of the Sun) causes metals to sink out of the atmosphere on time-scales much shorter than their cooling ages (the time since the formation of the white dwarf), leading unavoidably to pristine hydrogen or helium atmospheres. Therefore any metals detected in the atmosphere of a white dwarf imply recent or ongoing accretion.

The existence of metal-polluted white dwarfs has been a conundrum for nearly a century, as accretion from the interstellar medium could explain neither the frequency, nor the composition of these stars (Friedrich et al. 2004; Farihi et al. 2010). The detection of an infrared excess around the white dwarf G29-38 (Zuckerman et al. 1987) was interpreted by Graham et al. (1990) as a dusty debris disk formed from the destruction of an asteroid or comet, years before the discovery of the first exoplanet.

Such a circumstellar reservoir of debris provides a natural explanation for the origin of the metals identified in optical and ultraviolet *Hubble*/FOS spectra of G29-38 (Koester et al. 1997). Asteroids approaching a white dwarf to  $\approx 1 R_{\odot}$  will be tidally disrupted (Jura 2003), and the compact geometrical scale of the debris disks has been dynamically confirmed (Gänsicke et al. 2006). The existence of planets in these systems, scattering asteroids towards the white dwarf, is implied by simulations (Debes et al. 2012), however, the direct detection of white dwarf planets remains observationally challenging.

## The frequency of white dwarfs with planetary systems

Given that the detection of metals in the atmospheres of white dwarfs is the unmistakable signpost of planetary debris accretion, the frequency of evolved planetary systems can be directly measured from spectroscopic surveys. Ground-based observations are almost exclusively sensitive to the Ca H/K lines in relatively cool and old white dwarfs. Using Keck and Very Large Telescope (VLT) high-resolution spectra, Zuckerman et al. (2003) detected Ca H/K absorption in  $\approx 25\%$  of a sample of 87 stars with a median cooling age of  $\approx 1$  Gyr.

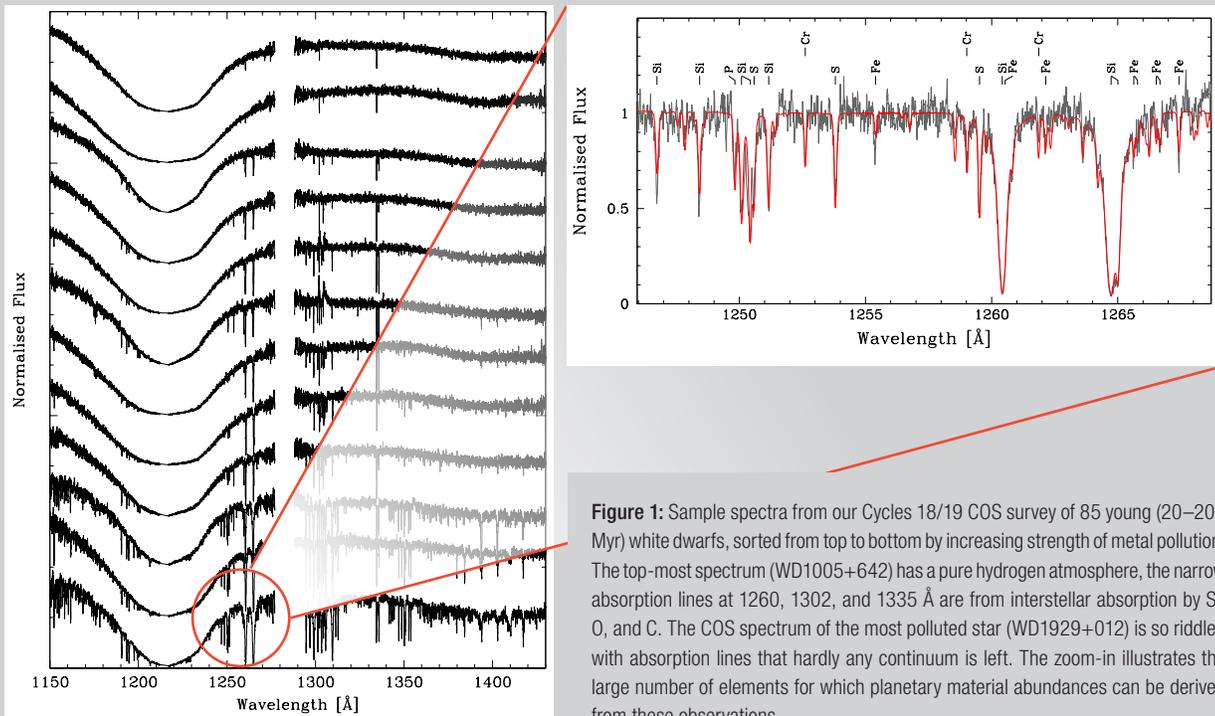
In younger, hotter white dwarfs, the Ca H/K lines become very weak as Ca II is ionized to Ca III. Probing the incidence of debris pollution at younger white dwarfs therefore requires far-ultraviolet spectroscopy, as this wavelength range is extremely rich in strong metallic transitions, in particular the Si II 1260/65 Å doublet.

Throughout Cycles 18/19, we carried out a COS survey of a representative sample of 85 white dwarfs with cooling ages of 20–200 Myr, and detected traces of heavy elements in 56% of these stars (Figure 1). Accounting for the effects of radiative levitation, i.e., the momentum of outgoing photons being absorbed in atomic transitions, we conclude that at least 27% of the stars in our sample must be currently accreting planetary debris (Koester et al. 2014).

Thus, so far there seems to be little evidence of an evolution in the rate of debris accretion as a function of cooling age, and the fraction of white dwarfs that host evolved planetary systems is overall comparable to the fraction of main-sequence stars with planets. Moreover, as many white dwarfs descend from 2–3  $M_{\odot}$  progenitors, this study also demonstrates the efficient formation of planetary systems around A-type stars.

Many simulations predict a peak in the dynamical activity of evolved planetary systems around 100 Myr cooling age (Debes et al. 2012, Mustill et al. 2014), though instabilities may occur in closely packed planetary systems even at very late stages in the evolution (Veras & Gänsicke 2015). We are





**Figure 1:** Sample spectra from our Cycles 18/19 COS survey of 85 young (20–200 Myr) white dwarfs, sorted from top to bottom by increasing strength of metal pollution. The top-most spectrum (WD1005+642) has a pure hydrogen atmosphere, the narrow absorption lines at 1260, 1302, and 1335 Å are from interstellar absorption by Si, O, and C. The COS spectrum of the most polluted star (WD1929+012) is so riddled with absorption lines that hardly any continuum is left. The zoom-in illustrates the large number of elements for which planetary material abundances can be derived from these observations.

now extending this study in an ongoing Cycles 22/23 COS survey to provide a seamless measure of the incidence of debris over the range 5–300 Myr.

### The bulk composition of exoplanetary systems

The known population of exoplanetary systems is growing at a breath-taking pace, and the focus is shifting from discovery to characterization. A property of key importance to our understanding of the formation of planetary systems is their bulk composition. In a pioneering paper, Zuckerman et al. (2007) realized that determining the photospheric abundances of debris-polluted white dwarfs is entirely analogue to learning about the abundances of planetary bodies in our solar system from the analysis of meteorites—“rocks that fell from the sky.”

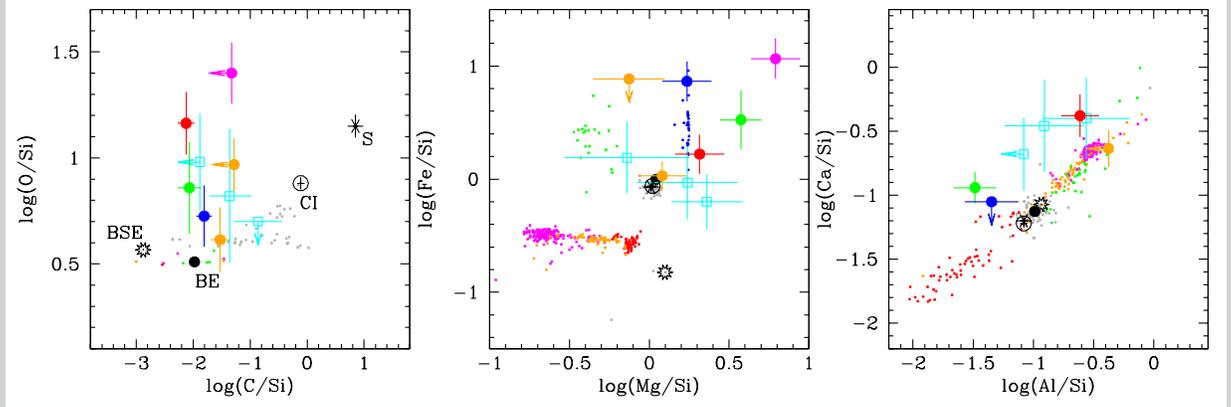
Taking into account the different velocities with which the various accreted elements diffuse through the white dwarf atmosphere (Koester 2009), it is possible to directly and accurately infer the bulk composition of extra-solar planetesimals from the measured photospheric abundances of the debris-polluted white dwarfs. The far-ultraviolet wavelength range is fundamental to these studies, and several groups have used *Hubble*/COS from Cycles 17 to 21 to analyze more than 15 metal-polluted white dwarfs. In zeroth approximation, the abundance patterns measured so far are overall similar to those of the terrestrial planets in the solar system, dominated by the major rock-forming elements (Si, Fe, Mg, and O), and volatile-depleted (Jura et al. 2012; Gänsicke et al. 2012).

At a closer look, the compositions measured in individual systems show a diversity similar to that of the different meteorite groups in the solar system, including Fe/Ni-rich differentiated parent bodies (Wilson et al. 2015), and collisional blending of asteroids (Xu et al. 2014). Our COS observations also identified debris from a water-rich planetesimal, that in its bulk composition resembles Ceres—the largest asteroid in the solar system (Farihi et al. 2013). Such planetary bodies may play an important role in the delivery of water onto rocky planets that formed dry.

Moving from the analyses of individual systems to ensemble studies of exoplanetary chemistry will provide important constraints for models of planet formation (Carter-Bond et al. 2012). *Hubble* and its ultraviolet spectrographs remain essential for this research over the coming years, and the increased sensitivity of large-aperture mission such as *HDST* has the potential to obtain accurate compositions for a few hundred planetary systems.

### White-dwarf debris disk studies in the era of *Webb*

*Spitzer* played a key role in identifying the current sample of nearly 40 dusty debris disks around white dwarfs (Rocchetto et al. 2015). Infrared spectroscopy of the brightest disks shows a mixture of minerals dominated by silicates (Reach et al. 2009; Jura et al. 2009). *Webb* will be able to obtain



**Figure 2:** The three panels illustrate a range of metal-to-Si number abundance ratios for several debris-polluted white dwarfs (big dots with error bars, from Gänsicke et al. 2012; Jura et al. 2012; Xu et al. 2013, 2014), compared to different families of meteorites (small dots, Nittler et al. 2004); the bulk Earth (BE) and bulk silicate Earth (BSE; McDonough 2000); the Sun (S; Lodders 2003); and CI chondrites (CI; Lodders 2003). The chemical abundances of planetary debris are, overall, similar to those of the inner solar system, being volatile-depleted (low C/Si ratio, *left panel*). The major rock-forming elements (Si, Fe, Mg, and O) show a wide range of relative abundances (*left and middle panel*), indicating thermal and collisional processing, with some evidence for differentiation. The relative ratio of the Ca and Al, which are confined to planetary crusts, remains unaltered by post-nebular processing.

high-quality mid-IR spectra for tens of white-dwarf debris disks, for which abundances measurements of the metal-polluted atmospheres will be already available from *Hubble* ultraviolet observations.

The diagnostic potential of these combined data sets is enormous, as it enables the detailed mineralogical modelling of the circumstellar dust, constrained by the precise knowledge of its bulk composition. The results from these studies will provide a wealth of observational insight into the formation and composition of rocky planets.

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