73. White dwarf pollution and exoplanets

A FASCINATING CONNECTION between the observed spectra of white dwarfs (the terminal evolutionary stage for 90–95% of the stellar population), and the formation and survival of exoplanetary systems, has been forensically assembled over the past two decades.

In his history of the field of heavy element pollution of white dwarf photospheres, Zuckerman (2015) suggests that the first observational evidence for the existence of exoplanet systems actually came more than a century ago from one such 'polluted' star, van Maanen 2 (van Maanen, 1917; 1919), although Dutch–American astronomer Adriaan van Maanen did not know that he had observed a white dwarf, nor of its significance!

Today, vMa 2 is considered to be the prototype of the white dwarf DZ spectral class, with high-resolution spectra showing that its atmosphere is deficient in hydrogen, and yet at the same time rich in the so-called 'refractory' elements, with lines of Fe, Ca, and Mg.

OTHER WHITE dwarfs with photospheric metals were duly discovered, with as many as 16 terrestrial-like heavy elements in the case of GD 362 (Zuckerman et al., 2007). It was soon appreciated that their intense gravity should cause any heavy elements to sink rapidly (Schatzman, 1945), with elements heavier than helium pulled into their interiors on time scales far shorter than their cooling ages (Fontaine & Michaud, 1979).

A replenishing source for these 'polluting' metals is therefore required. Initially, accretion from the interstellar medium was favoured (e.g. Farihi et al., 2010), although further observations (e.g., Zuckerman & Becklin, 1987), and theoretical work (e.g., Jura, 2003) shifted the accretion paradigm to rocky asteroidal debris.

Studies have since suggested that heavy elements in isolated white dwarfs with $T_{\rm eff} \sim 5000 - 20\,000$ K is evidence for the presence of a wide-orbit planetary system, generally comprising a rocky debris belt and at least one planet (e.g. Mustill et al., 2014). The planet's gravitational field perturbs the asteroid orbits, so that rocky asteroidal material is occasionally accreted onto the white dwarf (e.g. Jura & Young, 2014; Chen et al., 2019).

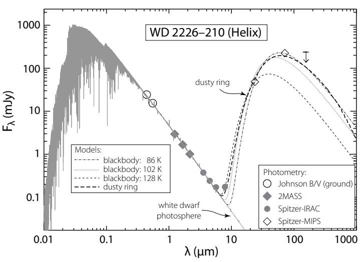
BEFORE CONTINUING to describe how Gaia is advancing the studies of white dwarf photospheric pollution, let me summarise a few points by way of background (see also Essay #29 on 'white dwarf surveys').

The first is that, while white dwarfs are extremely common in the solar neighbourhood, their very low luminosities means that any survey completeness falls rapidly with increasing distance, even within 20–50 pc. Pre-Gaia surveys listed around 20–30 000 known objects, with around 200 within 200 pc, while some 260 000 candidates have been identified from Gaia DR2.

Whether planetary companions to white dwarfs exist, having survived the red giant branch and asymptotic giant branch phases, will depend on things like the initial orbit separation and the stellar mass-loss rate. Many 'survival studies' have been made. For example, orbits with initial radii above about 0.7 au will remain larger than the stellar radius at all evolutionary stages, and white dwarfs could therefore potentially host surviving planets with orbital periods above about 2.4 years.

MEANWHILE, DUST DISKS around white dwarfs were first discovered in the early 1990s (Graham et al., 1990). Their presence is inferred from their large mid-infrared spectral excess. Major advances in their discovery and characterisation has been made from space, notably with Spitzer, and more recently WISE, and some 100 or more dust-disk systems are known today.

WD 2226–210, at the centre of the Helix planetary nebula, has been suggested as a prototype. Observed with Spitzer, the dust ring extends 35–150 au from the central white dwarf (interior to the helix structure), has a total mass of about one tenth Earth's, and is inferred to be replenished through collisional fragmentation of planetesimals (Dong et al., 2010).



Su et al. (2007)

The model favoured today attributes the heavy element pollution in white dwarf atmospheres to the accretion of rocky planetesimals which have been scattered into the tidal disruption radius of the white dwarf, where they are torn apart into dusty debris that subsequently spreads out to form a circumstellar disk. Some of this material can be perturbed by a planetary body, to be intermittently accreted by the white dwarf.

Indeed Farihi et al. (2012) eloquently described metal-enriched white dwarfs as representing astrophysical 'traps' for exoplanet debris, *'...acting as detectors that can yield the bulk composition of planetary building blocks that orbit intermediate-mass stars'*.

Drawing on models of accretion and sinking rates, they estimated that the 'high-rate' accretion time scale is less than 1000 years, such that a search of 10 000 DA stars would be needed to detect one in a high state lasting 100 yr. They argued that if Gaia provides some 10 000 metal-polluted candidates, then it may be possible to identify a single white dwarf accreting in a high state.

Current observations and models go further. Accreted photospheric compositions typically resemble that of bulk Earth, with at least 85% by mass in O, Mg, Si, and Fe.

Detailed results suggest that differentiation, leading to Fe-rich cores and Al-rich crusts, is common amongst Earth-mass exoplanets. It may follow that some white dwarfs might reflect purely crustal-like material, in which Si and O are the dominant pollutants.

Jura et al. (2014) even suggest that an indirect search for exoplanetary plate tectonics is possible because of a unique spectral signature in an externally polluted white dwarf signalled by the abundances of Ca, Sr and Ba.

The debris disks themselves can be recognised as a reprocessed infrared flux in excess of what is expected from an isolated white dwarf. About 1–3 per cent display this infrared dust-emission signature.

But a small subset of these already rare systems also display line emission, typically strongest in the Ca II 860 nm triplet, due to the presence of a gaseous disk component. These Doppler-broadened emission features are found to be largely consistent with models for gas in Keplerian orbits in a flat disk.

Where information on the spatial distribution of the gas is available, it appears to be co-located with the dust. These findings in turn imply that some mechanism must keep generating the gas, which would otherwise re-condense on time scales of months.

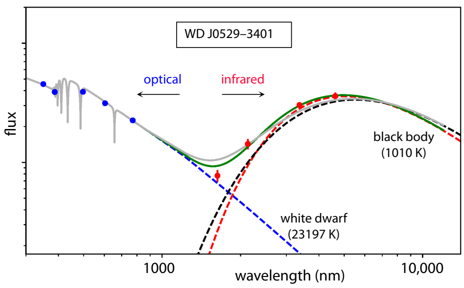
But the exact process underlying the generation of such circumstellar gas remains uncertain, and different scenarios have been proposed, including dust sublimation at the inner edge of the debris disk followed by subsequent radial spreading, and collisional cascades grinding the debris into gas.

Although these gaseous systems are therefore important for understanding the formation and evolution of planetary debris disks, their rarity is a barrier to further advances. Estimates suggest that only about 4 per cent of white dwarfs with dusty debris disks, or less than 0.1 per cent of all white dwarfs, display emission features from a gaseous component (Manser et al. 2020).

In the first statistical study using the Gaia data, (Manser et al. 2020) selected 7705 single white dwarfs from the Sloan Digital Sky Survey, and with Gaia magnitudes brighter than 19 mag. They identified five gaseous disk hosts, all of which had been previously discovered.

Restricting the 260 000 white dwarfs identified in the Gaia DR2 release by Gentile Fusillo et al. (2019) to those brighter than $G = 18.5$ mag, using the Gaia distances to constrain the models of the spectral energy distribution, and with infrared data from large area surveys (including 2MASS, UKIRT, VHS, and WISE), Gentile Fusillo et al. (2021) identified a further six white dwarfs with gaseous debris disks, bringing the total number known to just 21.

Amongst their new Gaia discoveries, WD J0846+5703 has an exceptionally strong infrared excess which contrasts with the standard model of a geometrically-thin, optically-thick dusty debris disk; WD J2133+2428 is the hottest gaseous debris disk host known, with an effective temperature of 30 000 K; and WD J0529–3401 (shown here) features a record number of 51 emission lines from five elements (H, Mg, Ca, Fe and O).



Gentile Fusillo et al. (2021)

Every Ca II triplet emitting system that has both multi-epoch observations and asymmetric emission profiles show morphological variability, and those that have been studied in detail have shown that the variations are periodic in nature, and well described by the precession of a fixed intensity profile in the disk.

The period of this precession can span the range of years to decades, and this range is supported by theoretical studies that show the effects of general relativistic precession and pressure forces on the gaseous disk.

The study and understanding of heavy element pollution of white dwarf photospheres is a fascinating subject still in its infancy. Gaia will undoubtedly be contributing to its advances over the coming years.