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Chromium, Nickel and Iron as clues to the formation histories of exoplanetary bodies

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Cr, Ni and Fe abundances trace the process of core-mantle differentiation. While Cr and Ni are both siderophilic (iron-loving), their exact abundances relative to Fe in both the core and the mantle depend on the conditions under which core-mantle differentiation occurs. We present a novel modelling approach in which we use observations of Cr, Ni and Fe found in exoplanetary bodies to deduce the conditions under which these bodies differentiated. These observations come from white dwarfs which have been polluted by the accretion of planetary material.

Polluted white dwarfs

A white dwarf is the compact remnant of a low mass star. They are stratified by their high surface gravity, such that the observable part of their atmosphere is typically pure H and/or He. Heavier elements sink through the atmosphere on short timescales (Koester 2009). However, we observe many white dwarfs whose atmospheres appear to be ‘polluted’ with such elements (e.g. Eisenstein et al. 2006, Hollands et al. 2017).

The remarkable implication is that material from substellar bodies, which have survived their host star’s main sequence lifetime, is being scattered on to white dwarfs (Farihi et al. 2010). These bodies range from asteroids (Jura 2003) to ice giant planets (Gänsicke et al. 2019).

Polluted white dwarfs therefore provide us with a unique opportunity to learn about the interiors of exoplanets and exoplanetesimals. Furthermore, we can gain insights into their formation histories, including core-mantle differentiation. This process occurs in rocky bodies throughout the solar system, from Earth and Mars to smaller objects like Vesta (De Sanctis et al. 2012). Polluted white dwarfs allow us to investigate whether this is also true of exoplanetary systems.

Some white dwarfs appear to have accreted relatively high amounts of elements such as Fe and Ni (e.g. PG0843, Gänsicke et al. 2012). These elements are siderophilic and on Earth are mostly found in the core. This is evidence that the pollutant originated in a body which underwent core/mantle differentiation. Collisional processing led to a core-rich fragment being scattered towards the white dwarf. The corollary of this observation, mantle-rich fragments enriched in elements such as Mg and Ca, has also been observed (Melis & Dufour 2017). Hollands et al. 2018 found that differentiation is a feature of exoplanetary systems based on the large proportion of polluted white dwarfs enriched in Ca or Fe relative to Mg. Bonsor et al. 2020 concluded that, given the improbable nature of observing signatures of differentiation, at least 60% of all polluted white dwarfs have accreted fragments of differentiated bodies.

Partitioning behaviour of Chromium and Nickel

The process of core-mantle differentiation does not always play out the same way, with different elements preferentially partitioning (i.e. moving) into the core or mantle to different extents depending on factors such as pressure, temperature and oxygen fugacity. The partitioning behaviour of Chromium and Nickel is determined by laboratory experiments. Studies such as Wade & Wood 2005, Corgne et al. 2008 and Fischer et al. 2015 subject a metallic starting material to high pressures and temperatures, inducing differentiation. The behaviour of each element can then be parameterised.

Chromium and Nickel exhibit evidence of different partitioning behaviour in the solar system. Relative to the Earth's core, Mars has a core enriched in Nickel and depleted in Chromium, and vice versa for the mantle and crust. This trend is consistent with differentiation at lower pressure (and hence lower temperature) and higher oxygen fugacity (Yoshizaki & McDonough 2020).

Chromium and Nickel are significant because not only do they display potentially detectable partitioning trends, but they have also been detected in the atmospheres of several white dwarfs. We aim to use these elements to constrain the formation conditions of white dwarf pollutants, and compare to pollution theories.

Bonsor et al. 2011 proposed a pollution scenario in which a white dwarf companion, distant enough to survive post-main sequence stellar evolution, scatters material from an exo-Kuiper belt towards the white dwarf. This theory predicts that the pollutants are small objects, and might be expected to display signatures of low pressure differentiation.

Harrison et al. 2020 presented a white dwarf pollution model in which differentiation always produces an Earth-like core, and found nine systems with Chromium and/or Nickel abundances which hint at non-Earth-like differentiation, further motivating our work.

Our work

We consider nine white dwarfs where Fe, Ca, Mg, Cr and/or Ni have been detected (Hollands et al. 2018). We aim to explain the observed abundances using a novel partitioning model, providing a best-fit core fraction for the accreted fragment and determining the conditions under which differentiation occurred. In particular, we constrain the pressure and oxygen fugacity. This builds on the work of Harrison et al. 2020 and allows us to provide crucial insights regarding the size of the parent bodies of the white dwarf pollutants.

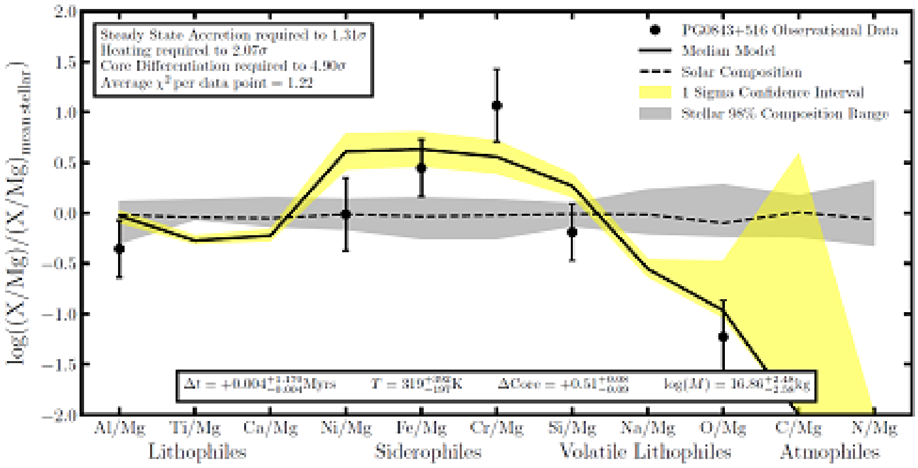

Figure 1: Data from PG0843+516, one of the 9 systems mentioned by Harrison et al 2020 in which the Cr and Ni abundances hint at non-Earth-like differentiation