Search for Metal Pollution in 81 DA White Dwarfs

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Abstract. A total of 82 DA white dwarfs have been observed with the Cosmic Origins Spectrograph on the Hubble Space Telescope in a snapshot program. The targets were selected to be in the Teff range from 17000 - 25000 K, where optical metal lines become weak and difficult to detect. Because of the strong Si, C, and O resonance lines in the UV, this survey has a sensitivity that is comparable to that of the Keck/VLT searches for CaII K in cooler white dwarfs. These objects also have no convection zone and thus very short diffusion timescales, assuring that accretion is currently ongoing. The spectra have high resolution and in most cases fairly good S/N. About 60% of them show photospheric metal pollution, predominantly of Si, but in some cases additional metals are present. We report the results of a preliminary analysis and discuss the sources of the accreted matter and the possible rôle of radiative levitation.

1. Introduction

Traces of heavy metals in helium-dominated atmospheres (spectral types DBZ, DZ) have been known since almost one hundred years – in fact, van Maanen 2, one of the three “classical” white dwarfs belongs to this class. Although the majority of WDs has hydrogen-dominated atmospheres (DA), the story of metal pollution in these objects is comparatively recent. Consisting for many years only of the prototype G74-7 (Lacombe et al. 1983), the second and third member of the class were only discovered in 1997 (Koester et al. 1997, Holberg et al. 1997). Since then the number has grown very fast to more than 100 today, including the ones reported here. This difference between helium and hydrogen atmospheres is purely observational bias: at the same abundance the equivalent width of the CaII resonance lines in helium is a factor of hundred or more larger than in a DA, due to the much larger transparency of helium at temperatures below 20000 K. Large telescopes like the VLT and Keck were therefore essential for this development.

Metals in these objects cannot be primordial. Gravitational settling with diffusion timescales of days to millions of years are always shorter than the evolutionary timescales, and an external source is required to replenish the heavy elements. Historically the standard explanation has been accretion from interstellar matter, although severe problems – notably the large underabundance of hydrogen in the accreted matter
and the absence of dense clouds in the solar neighborhood – were known and discussed since decades.

With the detection of an infrared excess around a significant fraction of the polluted objects by the Spitzer Space Telescope and other ground-based IR telescopes the explanation has now completely shifted towards the accretion from circumstellar dust in a debris disk, originating from the tidal disruption of rocky material from a planetary system. This offers a completely new method to study the elemental composition of extrasolar planetary systems by relating the photospheric abundances in the white dwarf to the abundances in the accreted matter using the equations of the accretion/diffusion scenario (e.g. Koester 2009).

For helium-rich and cool hydrogen-rich white dwarfs with extended outer convection zones the diffusion timescales can be of the order of a million years and the current status remains uncertain – beginning accretion, equilibrium between accretion and diffusion, or accretion already ended – with corresponding uncertainties for the composition of the accreted matter. We (PI Boris Gänsicke) have therefore initiated a program to observe a large number of DA white dwarfs with effective temperatures between 17000 and 25000 K with the COS spectrograph on the HST (implemented as a snapshot program). These DAs have no outer convection zones, the diffusion timescales are extremely short and equilibrium between accretion and diffusion is guaranteed. The atmospheric abundances together with diffusion velocities calculated from the atmosphere models directly give the diffusion flux for each observed heavy element and thus the relative abundances in the accreted matter.

The wavelength range observed was 1130-1435 Å, with typical exposure times of 1000 s. This range includes strong lines of Si and C, and fairly strong lines of other important elements like O, Al, S, Fe. Results for four heavily polluted objects have been published in Gänsicke et al. (2012) and details of the observations, parameter determinations, and synthetic spectra calculations can be found there. Here we report on 78 additional DAs, but include the first four in the statistics and figures.

2. Interstellar absorption

All objects show interstellar absorption lines of Si and C, and most additionally from N, S, O, Fe. The most direct indication is the Siii 1260 line and the absence or weakness of Siii 1265. The latter line has the larger gf value, but its lower level is 0.036 eV above the real ground level; it is always the stronger line in the stellar photosphere, but never appears as interstellar line in our sample. In most cases the photospheric lines (if present) are also shifted by 0.1-0.3 Å relative to the ISM lines.

The spectral resolution of ≈ 17 km/s does not allow to identify individual components in the ISM lines. However, the equivalent width of the ISM Siii 1260 line ranges from 21 to 184 mA, corresponding to column densities of $10^{12} - 8.8 \times 10^{12}$ cm$^{-2}$, if interpreted as single line on the linear part of growth (e.g. Savage & Sembach 1996). These column densities are typical values for the local interstellar cloud (LIC) surrounding our solar system (Redfield & Linsky 2004); very likely this is the only absorbing ISM material between us and most of our sample.
3. Photospheric metal absorption

49 of 82 or 60% of our objects show photospheric Si, 18 additionally C, and 8 further metals. Taken at face value this number is surprisingly high, as previous estimates (e.g. Zuckerman et al. 2003) put it much lower at 20-25%, and the clear signature of the connection with a planetary system, the infrared excess of a debris disk, is only found in about 1% of white dwarfs (Debes et al. 2012). Since the diffusion timescales are only a few days, the natural assumption would be that all these objects are currently accreting, with accretion fluxes for silicon within a factor of 10 of $3 \times 10^5$ g/s. However, before accepting such a conclusion, there is a caveat. Chayer & Dupuis (2010) have shown that some elements, in particular Si and C, can be supported by radiative acceleration in the atmosphere even at $T_{\text{eff}}$ as low as 20000 K. This would mean that no current accretion is needed, or that the accretion flows can be much smaller than calculated from the abundances.

![Graph](image-url)

Figure 1. log [Si/H] as a function of the parameter, which describes the efficiency of radiative levitation (see text). Upper curve with (red) squares are predicted abundances for 5 white dwarfs or models, lower curve with (blue) squares are the same data shifted by -0.4 dex. Larger circles are observed Si abundances, the smaller circles upper limits. The grey cross in the upper right corner indicates typical errors.

Fig. 1 shows the Si abundances as a function of a parameter calculated from the photon flux ($\log F_\lambda$) minus the surface gravity $\log g$. We take this as a qualitative measure of the radiative acceleration on Si, acting against the downward gravitation. Unfortunately, Chayer & Dupuis (2010) publish details only for one model with
$T_{\text{eff}} = 20000 \, \text{K}, \log g = 8$, but predicted abundances for four real stars can be extracted from a companion paper (Dupuis et al. 2010).

All upper limits fall below these predictions. The interpretation in this scenario is that these stars have never had Si in their outer layer, or lost it long ago either by downward gravitational settling or expulsion via a stellar wind. The other side of the coin is the conclusion that ALL objects currently showing photospheric Si must have accreted fairly recently (after levitation became effective enough to prevent settling) or are accreting right now. There are a large number of abundance measurements below the equilibrium line, which cannot be understood taking the theoretical and observational data at face value. We note, however, that a better agreement within the abundance errors for these objects could be achieved by shifting the prediction downward by about 0.4 dex. A reason for such an apparent discrepancy can easily be found. Fig. 3 in Chayer & Dupuis (2010) predicts very strong abundance gradients within the atmosphere, whereas our analysis only uses homogeneous distributions without radiative levitation. A real test of the levitation predictions could only be done by incorporating the effect in the model atmospheres and calculate the expected spectra. Whatever the explanation of such a shift, it would explain the majority of the Si observations with Si accretion rates $< 100 \, \text{g/s}$.

15 - 20 objects would remain above the predictions. These could only be explained by ongoing accretion from circumstellar material and the accretion rates as determined by the simple description without levitation would give correct results.

![Figure 2](image)

**Figure 2.** Mass flux ratios $\log [\text{C}/\text{Si}]$ as a function of Si mass flux in g/s. Larger circles are observed abundances, smaller circles upper limits. The dashed upper (red) line is the solar ratio, the lower (blue) line the data for Bulk Earth.
3.1. Carbon to silicon ratio

There are much fewer objects with C abundance determinations. The data in Dupuis et al. (2010) strongly suggest that carbon should not be supported in the atmosphere at lower $T_{\text{eff}}$. Yet there are 18 cases of observed photospheric C, similar to the number of clear accretion cases in the discussion of Si. Again, the only viable explanation for these seems to be ongoing accretion.

Fig. 2 shows the carbon to silicon ratio or upper limits, as well as those numbers for the sun and Bulk Earth. There are some values close to the solar/ISM value (possibly accretion from a low mass companion?) but the majority are a factor of 10 or more below solar. Gänsicke et al. (2012) found that the C/Si ratio of all four objects was close to the Bulk Earth value (in fact the four lowest points in the Fig. 2 are from that paper). It should be noted here that the Si abundance is generally much lower in the new objects and with a Bulk Earth ratio carbon would not be seen in these objects (as is shown by the many upper limits). The empty lower left part of the figure is thus probably observational bias. That the upper right part is also empty indicates that very high accretion rates occur only with carbon depleted matter.

3.2. Source of accreted matter

The accretion rates in the 15 - 20 objects clearly above the predicted levitation abundances are also too high to be explained by accretion from the thin interstellar matter in the local bubble around the sun. In view of the established connection between infrared excess, circumstellar dust, and metal pollution in the stellar atmosphere, the most likely explanation seems to be accretion from a debris disk.

However, that is not necessarily true for the majority of polluted DAZ. If the levitation calculations are qualitatively correct, the amount of Si necessary to explain the observations can be extremely small. The total mass in a 20000 K, log $g = 8$ atmosphere above $\tau_{\text{Ross}} = 1$ is approximately $10^{17}$ g. Using data from Fig. 3 in Chayer & Dupuis (2010) the maximum abundance in the outer layers of such a model is $n(\text{Si})/n(\text{H}) = 10^{-8}$, and therefore the mass of Si is smaller than $5.6 \times 10^{10}$ g.

The cross section for Eddington accretion from interstellar matter, which is the minimum we would expect, is

$$a = \frac{2GM_{\text{wd}}}{v^2} R_{\text{wd}} = 5.06 \times 10^{22} \text{ cm}^2$$

with white dwarf mass and radius $M_{\text{wd}}$ and $R_{\text{wd}}$, gravitational constant $G$ and space velocity $v$ (assumed to be 30 km/s). Assuming the white dwarf crosses just one tiny cloud like our Local Interstellar Cloud (LIC) with a Si column density of $10^{13}$ cm$^{-2}$, it would sweep up $4.7 \times 10^{13}$ g of Si. That is orders of magnitude more than needed to explain the observations, which would in this scenario diffuse downward, except for the tiny fraction supported by radiative levitation.

4. Conclusions

All 82 objects show interstellar absorption, very likely due to the local interstellar cloud (LIC) surrounding the solar system. More importantly, 60% also show photospheric Si, and a smaller fraction also C and a few other metals. If the predictions of radiative levitation are correct, the majority could be explained by very low accretion rates that
could be possible even within our local bubble. That leaves about 20% definitely ac-
creting from circumstellar material, in agreement with previous estimates. The carbon
to silicon ratio is very low (similar to B.E. values) in the cases of high accretion rates,
and shows a range of values for the lower rates, although mostly below the solar ratio.

References
Chayer, P., & Dupuis, J. 2010, in American Institute of Physics Conference Series, edited by
K. Werner, & T. Rauch, vol. 1273 of American Institute of Physics Conference Series,
Debes, J. H., Walsh, K. J., & Stark, C. 2012, ApJ, 747, 148. [1201.0756]
Dupuis, J., Chayer, P., & Hénault-Brunet, V. 2010, in American Institute of Physics Conference
Series, edited by K. Werner, & T. Rauch, vol. 1273 of American Institute of Physics
Conference Series, 412
Gänsicke, B. T., Koester, D., Farihi, J., Girven, J., Parsons, S. G., & Breedt, E. 2012, MNRAS,
Holberg, J. B., Barstow, M. A., & Green, E. M. 1997, ApJ, 474, L127
Koester, D. 2009, A&A, 498, 517. [0903.1499]
Koester, D., Provencal, J., & Shipmann, H. L. 1997, A&A, 320, L57
Lacombe, P., Wesemael, F., Fontaine, G., & Liebert, J. 1983, ApJ, 272, 660
Redfield, S., & Linsky, J. L. 2004, ApJ, 602, 776. [arXiv:astro-ph/0310878]
Savage, B. D., & Sembach, K. R. 1996, ARA&A, 34, 279
Zuckerman, B., Koester, D., Reid, I. N., & Hünsch, M. 2003, ApJ, 596, 477