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Rocky planetesimals as the origin of metals in DZ stars

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ABSTRACT

The calcium and hydrogen abundances, Galactic positions and kinematics of 146 DZ white dwarfs from the Sloan Digital Sky Survey are analyzed to constrain the possible origin of their externally polluted atmospheres. There are no correlations found between their accreted calcium abundances and spatial - kinematical distributions relative to interstellar material. Furthermore, two thirds of the stars are currently located above the Galactic gas and dust layer, and their kinematics indicate multi-Myr residences in this region where interstellar material is virtually absent.

Where detected, the hydrogen abundances for 37 DZA stars show little or no correlation with accreted calcium or spatial - kinematical distributions, though there is a general trend with cooling age. It is found that Eddington type accretion of interstellar hydrogen can reproduce the observed hydrogen abundances, yet simultaneously fails to account for calcium. The calcium-to-hydrogen ratios for the DZA stars are dominated by super-solar values, as are the lower limits for the remaining 109 DZ stars. All together, these polluted white dwarfs currently contain $10^{20\pm2}$ g of calcium in their convective envelopes, commensurate with the masses of calcium inferred for large asteroids.

A census of current $T_{\rm eff} \lesssim 12\,000$ K, helium-rich stars from the Sloan Digital Sky Survey suggests the DZ and DC white dwarfs belong to the same stellar population, with similar basic atmospheric compositions, effective temperatures, spatial distributions, and Galactic space velocities. Based on this result, pollution by the interstellar medium cannot simultaneously account for both the polluted and non-polluted sub-populations. Rather, it is probable that these white dwarfs are contaminated by circumstellar matter; the rocky remains of terrestrial planetary systems.

In this picture, two predictions emerge. First, at least 3.5% of all white dwarfs harbor the remnants of terrestrial planetary systems; this is a concrete lower limit and the true fraction is almost certainly, and perhaps significantly, higher. Therefore, one can infer that at least 3.5% of main-sequence A- and F-type stars build terrestrial planets. Second, the DZA stars are externally polluted by both metals and hydrogen, and hence constrain the frequency and mass of water-rich, extrasolar planetesimals.

Key words: circumstellar matter— minor planets, asteroids— stars: abundances— stars: chemically peculiar— stars: evolution— planetary systems— white dwarfs

1 INTRODUCTION

The curious presence of heavy elements in the atmospheres of cool white dwarfs has been known since the discovery of the first degenerate stars; van Maanen 2 is the prototype DZ white dwarf (van Maanen 1917). For more than half a century it has been understood that, in the absence of radiative forces, elements heavier than hydrogen and helium should rapidly sink below the photosphere in the high gravity environment of white dwarfs (Schatzman 1948); hence metal-lined white dwarfs like vMa 2 must be externally polluted.

Owing to a relatively low atmospheric opacity, the detection of calcium in the optical spectra of more than one dozen cool, single, helium-rich (DZ) white dwarfs preceded the availability of 8 m class telescopes and high resolution CCD spectrographs (Sion et al. 1990b). Although the sinking timescales are always orders of magnitude shorter than the white dwarf cooling age, heavy elements can persist for up to 10^6 yr in the sizable convection zones of helium-rich degenerates (Paquette et al. 1986). This fact led somewhat naturally to the hypothesis that the source of the accreted heavy elements was the interstellar medium (ISM), encountered in sufficient density a few to several times per Galactic orbit (on average) for the Solar neighborhood (Dupuis et al. 1993a,b, 1992).

Several factors have continually challenged the ISM pollution scenario. First, the typical dearth of hydrogen relative to calcium in DZ stars argues for the accretion of volatile depleted material (Dufour et al. 2007; Wolff et al. 2002; Sion et al. 1990a). Second, the firm establishment of the hydrogen-rich DAZ spectral class, with heavy element diffusion timescales as short as a few days, and Galactic positions far from known interstellar clouds (Koester et al. 2005a; Zuckerman et al. 2003). Third, the increasing number of metal-contaminated white dwarfs with infrared excesses and closely orbiting rings of dusty and gaseous debris (Farihi et al. 2009; Jura et al. 2009a; Gänsicke et al. 2008). Thus, while there is firm observational evidence of pollution via circumstellar material, as yet there is none favoring the ISM.

Aannestad et al. (1993) provided an extensive spatial, kinematical, and calcium abundance analysis against which they tested likely scenarios of interstellar accretion based on the best available data at that time, concluding interstellar accretion could not explain the abundances in *any* of their 15 DZ white dwarfs. However, their landmark study was limited to targets within 50 pc for the most part, and to stars that were proper-motion selected, and hence biased toward higher space velocities (Sion et al. 1988). Kilic & Redfield (2007) examined possible correlations between the current positions of 35 DAZ white dwarfs and models of the surrounding ISM as inferred from nearby column density measurements, finding a lack of sufficient material to account for most polluted stars.

This paper returns to the question of the origin of the DZ spectral class. Historically, the DZ stars outnumbered their hydrogen-rich counterparts stars by 25:1 (Dupuis et al. 1993b) until high resolution, spectroscopic searches with large telescopes uncovered a commensurate number of DAZ stars (Koester et al. 2005a; Zuckerman et al. 2003). Today, the ratio of known DZ to DAZ stars is greater than 4:1, due almost exclusively to the Sloan Digital Sky Survey (SDSS; Eisenstein et al. 2006). The ability to detect mild levels of heavy element pollution in these stars, combined with the relative lack of circumstellar material at both the DZ and cool DAZ white dwarfs (Farihi et al. 2009), makes the origin of the DZ stars challenging to constrain.

It is argued here that the hundreds of newly identified, cool, helium-rich white dwarfs from the SDSS provide an excellent, spatially and kinematically unbiased sample upon which to test the ISM accretion hypothesis. These stars form a large statistical sample that favors an alternative to the accretion of Galactic gas and dust; as a whole the SDSS DZ stars do not show the spatial, kinematical, or elemental abundance correlations expected from accretion episodes within the plane of the Galaxy. Furthermore, the SDSS DZ and DC (helium-rich, featureless) stars appear to be similar populations of polluted and non-polluted stars broadly sharing all relevant characteristics save photospheric calcium, and perhaps hydrogen.

2 COOL HELIUM-RICH WHITE DWARFS FROM THE SDSS DR4

The SDSS fourth data release (DR4; Adelman-McCarthy et al. 2006) contains a prodigious number of new white dwarfs, in the neighborhood of 6000 (Eisenstein et al. 2006). Excluding multiple entries for the same source, binaries or binary candidates, and uncertain classifications, there are 95 DZ and 142 DC stars within the DR4 white dwarf catalog. Under further scrutiny, Dufour et al. (2007) has expanded the number of confirmed, unique DZ stars to 146, providing effective temperatures, calcium abundances, and photometric distances under the assumption of $\log[g\,(\mathrm{cm\,s^{-2}})] = 8.0$. Of these 288 cool, helium-rich white dwarfs in DR4, only one was known previously; G111-54 or SDSS J080537.64+383212.4 (Dufour et al. 2007; Greenstein 1975).

Perhaps surprisingly, the current number of DC and DZ stars in the SDSS are nearly identical. The DR4 catalog `autofit` temperatures for helium-rich stars are generally unreliable near or below 10 000 K, as their helium atmosphere models do not extend below this temperature (Eisenstein et al. 2006). Owing to this fact, the DC star spectroscopic and photometric data were fitted using the same technique and helium-rich (metal-free) models as in Dufour et al. (2007), yielding effective temperatures and photometric distances, again assuming $\log g = 8.0$. All photometric data were taken from the DR4 white dwarf catalog (Eisenstein et al. 2006), with stellar parameters for the DZ stars from Dufour et al. (2007) and the DC model fits performed for this work.

Spatial and kinematical data for these white dwarfs were obtained from the SDSS seventh data release (DR7; Abazajian et al. 2009). This latest data release includes the USNO-SDSS derived proper motion catalog of Munn et al. (2004) and its recent amendments (Munn et al. 2008), with statistical errors around 3 $\mathrm{mas\,yr^{-1}}$. For a handful of white dwarfs, proper motions were not available in the DR7 catalog; for these stars measurements were taken from the SuperCOSMOS Science Archive (SSA; Hambly et al. 2001), the LSPM catalog (Lepine & Shara 2005), or were calculated for this work based on two or more positions on archival photographic plates and SDSS images separated by approximately 50 years. These proper motions are listed in Table 1.

3 ABUNDANCE ANALYSIS

The SDSS white dwarfs offer a deeper snapshot of the Solar neighborhood and beyond. Owing to the $g > 22$ AB magnitude limit of the survey, and its general avoidance of the Galactic plane, these white dwarfs typically represent distant stars (tens to hundreds of pc) at intermediate Galactic latitudes. Hence the SDSS DZ stars are an excellent probe of the local ISM (LISM) both within and beyond the Local Bubble or Chimney (Welsh et al. 1999, 1994), which extends roughly to 100 pc (Redfield & Linsky 2008).

A number of relevant quantities were calculated from the DZ and DC white dwarf spatial and kinematical data: tangential speed v_{tan}, height above (or below) the Galactic mid-plane $|z|$, space velocities UVW (assuming zero radial

Table 1. White Dwarf Proper Motions Unavailable in SDSS DR7

SDSS White Dwarf	μ (mas yr^{-1})	P.A. (deg)	Sources
J000557.20+001833.3	209.3	93.5	1,2,3
J020001.99+004018.4	33.2	87.7	1
J020132.24−003932.0	90.7	184.1	1
J080211.42+301256.7	59.4	199.8	3
J082927.85+075911.4	168.0	258.7	1
J083434.68+464130.6	225.1	133.2	1,2,3
J084911.86+403649.7	96.3	233.8	1
J093545.45+003750.9	66.2	227.0	1
J094530.20+084624.8	67.4	255.7	1
J113711.28+034324.7	176.5	230.3	2,3
J122204.48+634354.5	66.6	251.1	1
J140316.91−002450.0	63.6	96.9	3
J144022.52−023222.2	224.3	271.8	3
J153032.05+004509.0	71.7	249.7	1

Sources: (1) SSA; (2) LSPM catalog; (3) this work.

Table 2. Statistical Properties of SDSS DZ and DC White Dwarfs

Parameter	146 DZ Stars	142 DC Stars
$T_{\rm eff}$ (K)	8700 ± 1330	9040 ± 1610
$g - z$	-0.29 ± 0.23	-0.18 ± 29
d (pc)	196 ± 91	206 ± 96
$\lvert z\rvert$ (pc)	140 ± 67	148 ± 72
$v_{\rm tan}$ (km s^{-1})	48 ± 32	52 ± 25
U (km s^{-1})	2 ± 35	-4 ± 38
V (km s^{-1})	-12 ± 28	-12 ± 24
W (km s^{-1})	1 ± 25	-1 ± 25
$\lvert W\rvert$ (km s^{-1})	18 ± 17	19 ± 15
T (km s^{-1})	43 ± 29	48 ± 23

Space velocities were calculated assuming zero radial velocity and corrected to the LSR (otherwise $T = v_{\rm tan}$).

velocity), and total space velocity $T^2 = U^2 + V^2 + W^2$. Space velocities were corrected to the Local Standard of Rest (LSR; Dehnen & Binney 1998), with U positive toward the Galactic anticenter, V positive in the direction of Galactic rotation, and W positive toward the north Galactic pole. In the absence of correction to the LSR, the assumption of zero radial velocity is equivalent to $T = v_{\rm tan}$. Tangential speeds were calculated from

$$v_{\rm tan}\,({\rm km\,s^{-1}}) = 4.7405 \times d\,({\rm pc}) \times \mu\,({\rm arcsec\,yr^{-1}}) \qquad (1)$$

The Sun does not have zero velocity relative to the LSR; depending on viewing direction, the Solar motion contributes $v_{\rm tan} = 10 - 15\,{\rm km\,s^{-1}}$ (Dehnen & Binney 1998; Mihalas & Binney 1981). Table 2 lists the calculated parameter means for the SDSS DZ and DC white dwarfs.

3.1 A Glance at the Data

As a first attempt to establish the relationship, if any, between the DZ stars and the ISM, one can search for spatial or kinematical correlations with calcium abundance (Zuckerman et al. 2003; Aannestad et al. 1993). Figure 1 plots the calcium abundances (throughout this paper [X/Y] = log [n(X)/n(Y)]), relative to helium, of the 146 DZ stars as a function of effective temperature, height above the Galactic mid-plane, and tangential speed. A low abundance cutoff at higher effective temperatures and larger distances is apparent in the upper and middle panels; these are observational biases arising from higher atmospheric opacities and lower spectroscopic sensitivity, respectively (Dufour et al. 2007; Koester et al. 2005a). The classical conundrum of the DZ white dwarfs presents itself well in the upper panel; the majority of stars have no detected hydrogen, including those with the highest calcium abundances.

The middle and lower panels of Figure 1 are noteworthy because they fail to reveal a physical correlation between accreted calcium and height above the Galactic disk or tangential speed. The Galactic gas and dust layer extends roughly 100 pc above the Galactic mid-plane, and yet some of most highly polluted DZ white dwarfs lie well above this region. The lower panel is relevant in the context of gravitationally driven accretion, expected if the DZ stars obtain their heavy elements while moving through the ISM. The lack of correlation between speed and the metal abundances argues, qualitatively but strongly, against fluid accretion of ISM.

Figure 2 plots the masses of calcium contained in the convection zones of these metal-enriched stars using their abundances together with the convective envelope masses for log $g = 8$ helium-rich white dwarfs (Koester 2009). The figure shows that the most highly polluted DZ stars currently harbor up to 10^{22} g of calcium in their convection zones. This is a truly remarkable amount of a single heavy element, a mass in calcium alone that is roughly equivalent to the total mass of a 200 km diameter asteroid(!). A more typical DZ star appears to contain around 10^{20} g of calcium, still a prodigious amount, and corresponds to a time-averaged metal accretion rate of $2 \times 10^8\,{\rm g\,s^{-1}}$ (Farihi et al. 2009), and a total accreted mass of metals of just under 10^{22} g.

Figure 3 plots the hydrogen abundances in 37 of the 146 DZ stars where hydrogen is detected or inferred (Dufour et al. 2007), versus height above the Galactic mid-plane and tangential speed. No obvious pattern is seen, although there may be a higher density of DZA stars near the Galactic disk and perhaps also toward more modest speeds, but the former may be an observational bias due to diminished spectroscopic sensitivity. In any case, one should expect a correlation between these quantities if the hydrogen were accreted from ISM.

As discussed by Dupuis et al. (1993a), white dwarfs accreting Solar abundance matter within the ISM at $3 \times 10^{11}\,{\rm g\,s^{-1}}$ for 10^6 yr can accumulate the heavy element mass fractions observed in the convective envelopes of DZ stars, such as plotted in Figure 2 (however, this cannot account for their hydrogen abundances, discussed in detail below). Yet some care must be taken not to invoke such high accretion rates without skepticism; while these rates are sufficient to account for the calcium data (that is the nature of the hypothesis), the physical plausibility is of equal importance. Below, the problem of interstellar accretion onto white dwarfs is reviewed in some detail and updated with old and new theoretical and empirical considerations.

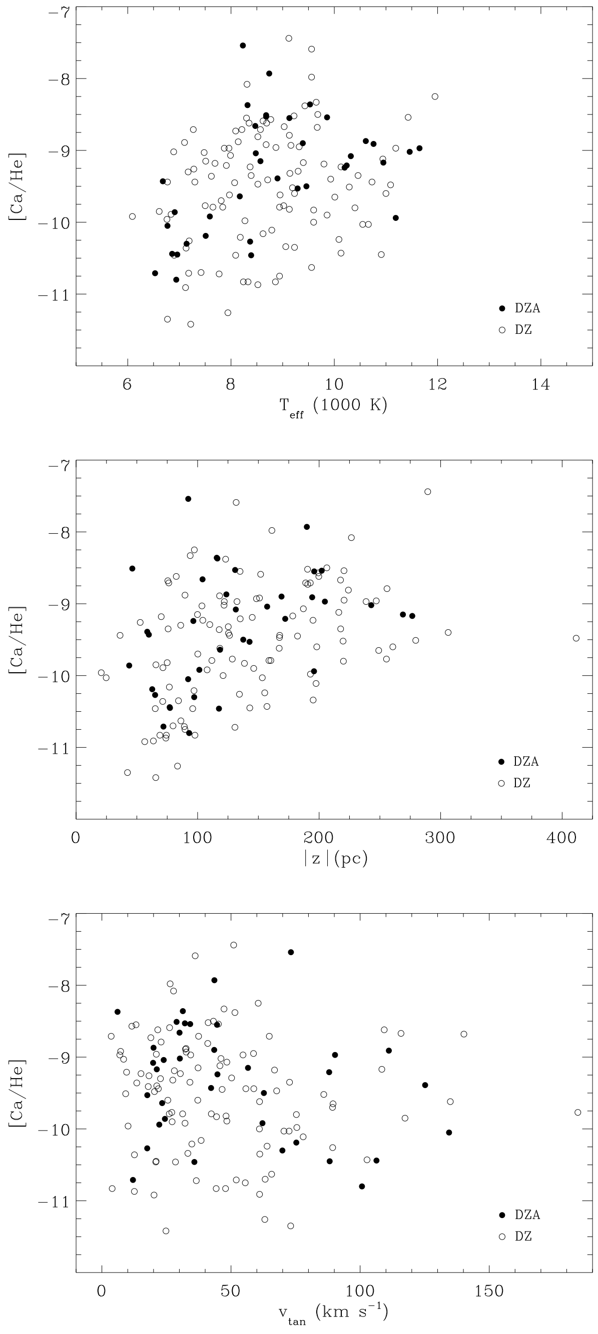

Figure 1. Calcium abundances for the 146 DZ stars plotted versus effective temperature, height above the Galactic mid-plane, and tangential speed. Those stars with detected hydrogen are plotted as filled circles, while those without are plotted with open circles.

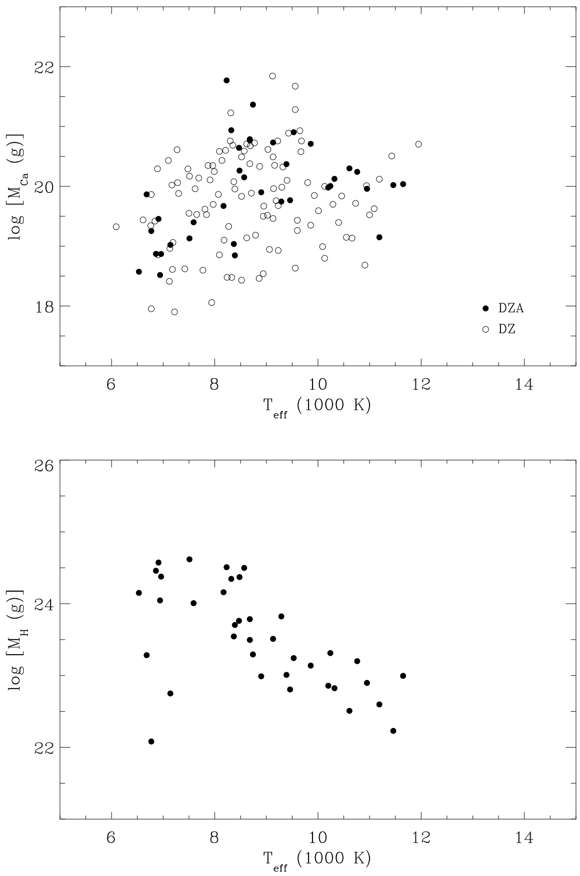

Figure 2. Mass of calcium and hydrogen in the convective envelopes of the SDSS DZ stars; envelope masses were taken from Koester (2009). A typical calcium mass in the convection zone of these stars is 6×10^{19} g, roughly the same as that contained in the asteroid Minerva, whose mean diameter is 146 km and total mass is 3×10^{21} g.

3.2 A Closer Look at the Interstellar Accretion Hypothesis: Hydrogen

Both Koester (1976) and Wesemael (1979) were among the first to consider the issue of interstellar accretion onto helium-rich white dwarfs, both concluding that the atmospheres of these stars (both type DB and DC) were *incompatible* with Bondi-Hoyle accretion of interstellar hydrogen. That is, in most cases a single interstellar cloud encounter lasting around 10^5 yr would suffice to transform a DB (or DC) star into a DA (Koester 1976). Therefore, the existence of more than 1000 hydrogen-poor white dwarfs in the SDSS (Eisenstein et al. 2006) argues strongly against the Bondi-Hoyle type accretion of interstellar hydrogen.

Regardless of particulars relevant only to the metal-enriched white dwarf varieties, the lack of hydrogen in helium atmosphere white dwarfs is of great observational significance. High resolution and high signal-to-noise spectroscopy reveals roughly equal numbers of DB stars where hydrogen is either undetected or detected but deficient by a few to several orders of magnitude relative to helium (Voss et al. 2007). The highest mass of hydrogen seen in a DB (metal-free) atmosphere is around 8×10^{22} g in a 12 000 K star, while the older and cooler counterparts studied here (the DZA stars) contain up to 4×10^{24} g. This higher mass of atmospheric hydrogen would be accreted in under 10^6 yr at the interstellar Bondi-Hoyle rate assumed by Dupuis et al. (1993a), and hence this cannot be the correct picture due to the lack of such hydrogen masses in DB stars.

Gravitational accretion of ISM particles by a star of mass M and radius R, in the supersonic regime follows the mathematical form (Alcock & Illarionov 1980)

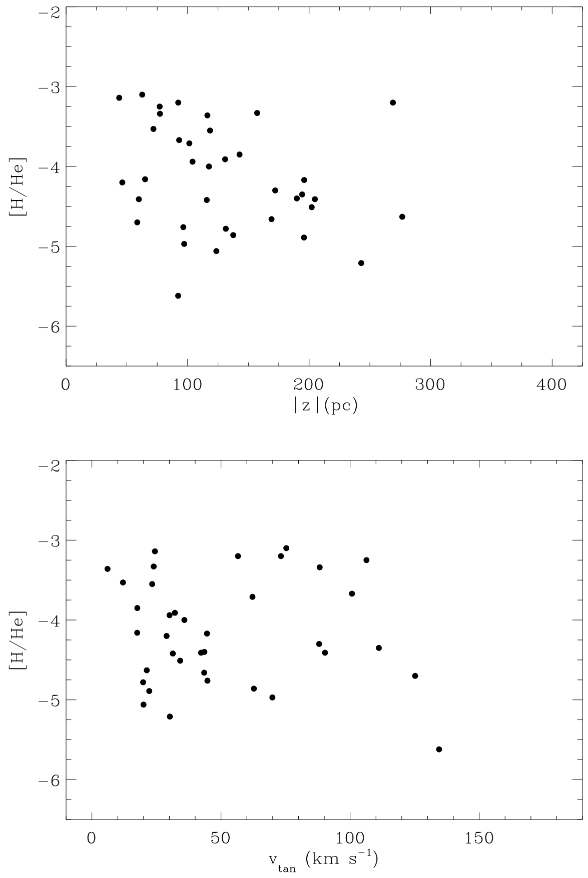

Figure 3. Hydrogen abundances for the 37 DZA stars plotted versus height above the Galactic mid-plane, and tangential speed.

$$\dot{M} = \pi \left(R_A + R\right) R s \rho_\infty \tag{2}$$

where R_A is the accretion radius, $s = \sqrt{v^2 + {c_s}^2}$ for relative stellar velocity v and ambient sound velocity c_s, while ρ_∞ is the unperturbed density of material being accreted. The accretion radius is defined as

$$R_A \equiv \frac{2GM}{s^2} \tag{3}$$

and is often referred to the as the Bondi or Bondi-Hoyle radius. For all possible speeds considered here, $R_A \gg R$, and the accretion rate is given by

$$\dot{M} = 2\pi G M R_A R s \rho_\infty \tag{4}$$

or

$$\dot{M}_{\rm Edd} = \frac{2\pi G M R \rho_\infty}{s} \tag{5}$$

This is the Eddington rate (Eddington 1926), the accretion induced on non-interacting particles by the geometrical-gravitational cross section of the star as it travels through the ISM.

Bondi-Hoyle theory (i.e. including gas pressure; Edgar 2004) demonstrates that the effective cross section in Equation 4, $\pi R_A R$ becomes $\pi {R_A}^2$ in the fluid dynamical limit (Bondi 1952), yielding an accretion rate for interacting particles

$$\dot{M}_{\rm BH} = \frac{4\pi G^2 M^2 \rho_\infty}{s^3} \tag{6}$$

This mass infall rate represents the maximal, idealized case where the mean free path of the particles is such that collisions are important and transverse momentum is effectively destroyed downstream from the star. It is also physically unrealistic in perhaps all situations excepting an ionized plasma, as it assumes no net angular momentum between the accreting star and its surrounding medium (Koester 1976), and it certainly does not apply to neutral atoms or large particles (Alcock & Illarionov 1980). The ratio of the Bondi-Hoyle to Eddington accretion rates is $v^2R/2GM$ for $v \gg c$, or around 10^4 for typical white dwarf sizes and speeds (Koester 1976). Table 3 lists typical densities and other relevant parameters for four fundamental types of ISM: molecular clouds, diffuse clouds, warm ionized, and hot ionized. Listed also are the expected high-end mass infall rates for white dwarfs moving through these regions following either Bondi-Hoyle (fluid) or Eddington (geometric) type accretion.

The two-phase accretion-diffusion scenario as laid out by (Dupuis et al. 1993a), invokes 10^6 yr within a cloud (accretion), and 5×10^7 yr between clouds (diffusion). For disk stars with Galactic orbits similar to the Sun, these timescales imply about five cloud encounters per 240 Myr orbit. The motions of interest are the relative motions between stars and the ISM, the latter which should be moving within the relatively low velocity spiral arms of the Galactic disk (Jahreiß & Wielen 1997).

If correct, this implies a typical helium-rich white dwarf moving at 50 km s^{-1} relative to the LSR and (presumably) the ISM travels, on average, 240 pc within clouds during a single Galactic rotation. This timescale corresponds to the cooling age for a $\log g = 8.0$, 14 500 K helium-rich white dwarf, and hence such a star should, according to this scenario, obtain up to 5×10^{22} g of hydrogen via geometric accretion, or [H/He] $= -4.4$. This value is commensurate with the highest hydrogen abundances observed in DB stars, and well above the lower limit of detectability (Voss et al. 2007).

This comparison implies 1) the densities and corresponding Eddington accretion rates in Table 3 are too high, or 2) cloud encounters last less than 10^6 yr or are less frequent than once per 5×10^7 yr, but is otherwise consistent with the geometric capture of hydrogen within the ISM, and inconsistent with fluid accretion. Ignoring the fact that all hydrogen will be ionized within the Bondi-Hoyle radius of the white dwarf, and hence should accrete as a plasma at the fluid rate (Alcock & Illarionov 1980), it is clear that fluid accretion of hydrogen does not occur in helium atmosphere white dwarfs, if and when passing through dense ISM.

3.3 Super-solar Calcium to Hydrogen Abundances

The average DZ star in the sample has an effective temperature of 9000 K and a cooling age around 860 Myr (Fontaine et al. 2001). A hydrogen abundance of [H/He] $= -3.8$ was detectable in all 146 DZ stars (Dufour et al. 2007), equivalent to a bit less than 10^{24} g of hydrogen at the average DZ temperature. In order to avoid such a hydrogen

Table 3. Representative High ISM Accretion Rates for White Dwarfs

ISM Type	Gas	ρ_∞ (cm^{-3})	T (K)	c_s ($\mathrm{km\,s}^{-1}$)	$\dot{M}_{\mathrm{BH}}$ ($\mathrm{g\,s}^{-1}$)	$\dot{M}_{\mathrm{Edd}}$ ($\mathrm{g\,s}^{-1}$)
Molecular Cloud	H_2	1000	20	0.3	10^{12}	10^{8}
Diffuse Cloud	H	100	80	1	10^{11}	10^{7}
Warm Ionized	H^+	1	8000	1	10^{9}	10^{5}
Hot Ionized	H^+	0.01	10^{6}	100	10^{7}	10^{3}

Accretion rates listed are order of magnitude estimates calculated for the listed parameters and $v = 50\,\mathrm{km\,s}^{-1}$, a speed typical of both the DZ and DC samples.

mass within its outer envelope, a helium-rich white dwarf must eschew 1) fluid accretion in any region similar to the relatively low density LISM for 99.9% of its cooling age, and 2) geometrical accretion in any molecular cloud, for around 90% of its cooling age. Only 12 of the DZ stars or 8% of the sample have hydrogen abundances [H/He] $\geqslant -3.8$, implying such avoidance has occurred for the remaining 134 DZ(A) stars. If the photospheric calcium originates in the ISM, then a process that accretes metal-rich dust grains while eschewing hydrogen (and other gaseous volatiles) is necessary to account for the DZ white dwarfs with little or no hydrogen.

Historically, the super-solar [Ca/H] abundances of DZ white dwarfs were qualitatively accounted for by preferential accretion of dust grains (Dupuis et al. 1993b). A hypothesis to permit the incursion of dust grains yet repulse light gas is the propeller mechanism, whereby charged ion species are repelled at the Alfvén radius (Wesemael & Truran 1982). This model fails to explain a number of very hydrogen-deficient DZ-type stars, including GD 40 with [H/He] $= -6.0$, a white dwarf for which Friedrich et al. (2004) failed to find evidence of magnetism sufficient to drive a propeller. Rather, in the same study the DZA star LHS 235, with 400 times more hydrogen than GD 40 was found to have a 7 kG magnetic field – essentially *the exact opposite* of what might be expected if hydrogen was screened efficiently by a propeller. Perhaps the coup de grâce for the propeller is the magnetic DZA star G165-7; with a 650 kG field, [Ca/He] $= -8.1$, and [H/He] $= -3.0$ (Dufour et al. 2006), it has everything a 'fan' could hope for. But should this star have so much hydrogen? According to theory, its propeller failed around 660 Myr ago as a 7500 K star (Wesemael & Truran 1982), and could have amassed at most 2×10^{24} g in 660 Myr of *continuous* accretion at the high Eddington rate, corresponding to [H/He] $= -4.0$. Clearly, this star was never a propeller. This mechanism is unsupported by observations (Friedrich et al. 2004), and is fundamentally at odds with the existence DBAZ and DZA stars (Voss et al. 2007).

The upper panel of Figure 4 plots the hydrogen versus calcium abundances of all 37 DZA stars. The lack of any correlation between the two elements suggests either 1) disparate origins, or 2) a common origin with intrinsic variations in [Ca/H]. Neither of these two possibilities is consistent with ISM accretion. The middle and lower panels of Figure 4 display the inferred [Ca/H] abundances and lower limits for the 37 DZA and 109 DZ stars. In both cases, the vast majority of these values are super-solar by at least an order of magnitude (see also Figure 12 of Dufour et al. 2007).

3.4 A Closer Look at the Interstellar Accretion Hypothesis: Metals

Interstellar gas – both cold and warm – is metal-poor; heavier elements tend to be locked up in grains, leaving only light and volatile elements (Venn & Lambert 1990). This fact was not considered by Dupuis et al. (1993a), whose accretion-diffusion scenario explicitly assumes 1) accretion based on fluid rates for hydrogen also apply to heavy elements, and 2) elements are accreted in Solar proportions. Above it was shown that fluid accretion rates for ISM accretion of hydrogen over predict the observed abundances in DB stars by a few to several orders of magnitude. But more importantly for heavy element accretion is the fact that *interstellar dust grains should not accrete at the fluid rate*.

Solid particles will follow trajectories independent of surrounding gas whether neutral, or charged and electrically or magnetically coupled to the gas (Alcock & Illarionov 1980). However, dust grains approaching the stellar surface will be separated into their constituent elements via sublimation that proceeds at slightly different rates according to the particular chemical species, resulting in significant ingress prior to becoming gaseous. The gradual evaporation of approaching interstellar dust has two major consequences. First, gaseous heavy elements cannot accrete at the fluid rate, as the effective gravitational cross section is significantly reduced by the close approach necessary for their evaporation out of grains. Second, the process of sublimation will spatially and temporally separate heavy elements according to their specific evaporation temperatures, resulting in preferentially higher accretion rates for volatile species such as ice mantles, as opposed to metallic atoms or refractory material. This latter consequence is interesting because it predicts a relatively high volatile to refractory element accretion mixture; in stark contrast both to the observed abundances and to those expected from the accretion of circumstellar material (Sion et al. 1990a).

The radius at which dust grains are evaporated, R_{ev}, and become part of the ambient, interacting gas is substituted for R in Equation 2 which then becomes (Alcock & Illarionov 1980)

$$\dot{M}_{\mathrm{gr}} = \pi \left(R_A + R_{\mathrm{ev}}\right) R_{\mathrm{ev}} s \rho_\infty \tag{7}$$

If the grains absorb and radiate energy as blackbodies, they will evaporate at temperature T_{ev} at a distance from the star given by (Chen & Jura 2001)

$$R_{\mathrm{ev}} \approx \frac{R}{2} \left(\frac{T_{\mathrm{eff}}}{T_{\mathrm{ev}}}\right)^2 \tag{8}$$

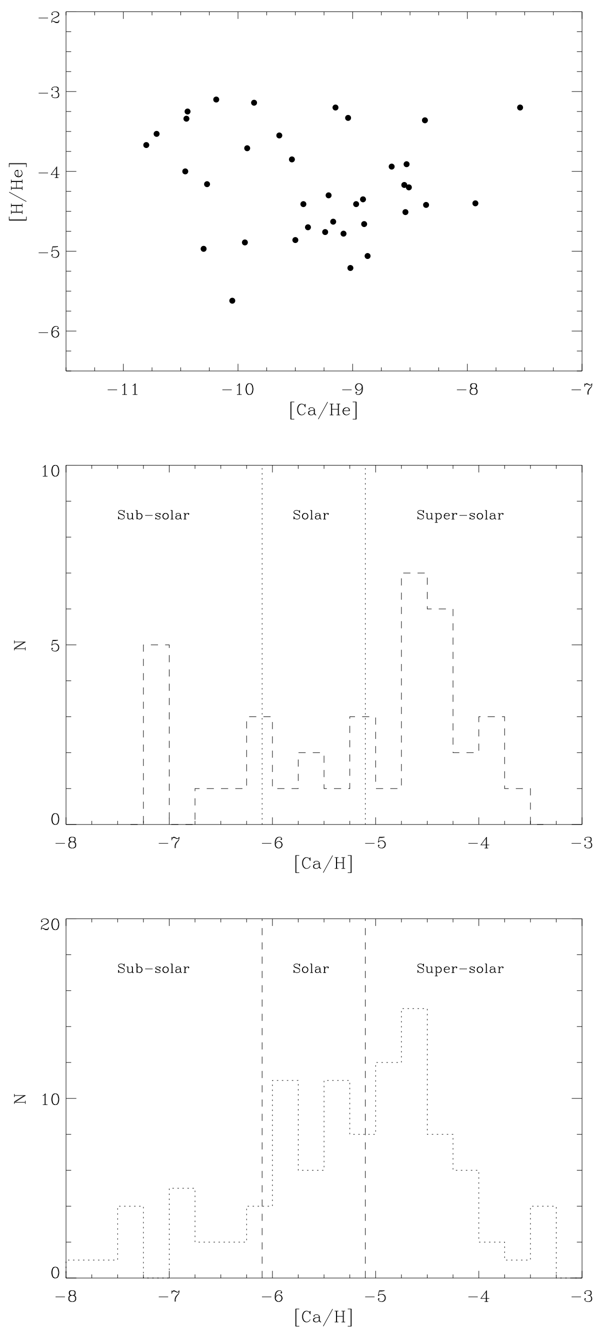

Figure 4. The upper panel plots the hydrogen versus calcium abundances for the 37 DZA stars, while the middle panel plots a histogram of their [Ca/H] ratios. The lower panel plots [Ca/H] ratio *lower limits* for the 109 DZ white dwarfs without detected hydrogen. The Solar abundance is [Ca/H] = −5.6.

Taking a typical DZ effective temperature of 9000 K from Table 3 and $T_{\rm ev}$ between 1500 and 2000 K, the resulting evaporation radius is between 10 and 18 white dwarf radii (or 0.13 to 0.23 $R_\odot$). This is a few hundred times smaller than a typical Bondi-Hoyle radius, around 0.5 AU for a white dwarf, and hence heavy elements will accrete at a rate much closer to the Eddington rate. In this situation $R_A \gg R_{\rm ev}$, and the resulting mass infall becomes

$$\dot{M}_{\rm gr} = \frac{\pi G M R \rho_\infty}{s}\left(\frac{T_{\rm eff}}{T_{\rm ev}}\right)^2 \qquad (9)$$

All else being equal, this rate should be around 10 to 18 times the Eddington rate for refractory-rich dust grains, such as interstellar silicates. As pointed out more than thirty years ago by Koester (1976), the above analysis ignores any net angular momentum between the star and the surrounding ISM, which will work to reduce the effectiveness of accretion excepting where material is fully ionized, a situation unlikely to be realized for gaseous heavy elements. The physical considerations discussed in this section have been, for the most part, overlooked in several major studies of DZ stars, and their absence has biased outcomes favoring the interstellar origin of metals in cool white dwarfs in general (Koester & Wilken 2006; Wolff et al. 2002; Friedrich et al. 2000; Dupuis et al. 1993b).

Applying Equation 8 to the highest density, Solar abundance ISM (i.e. a dust to gas ratio of 1:100, [Ca/H] = −5.6, $\rho_\infty = 1000\,{\rm g\,cm^3}$), a white dwarf can accrete heavy elements from the ISM at up to $2 \times 10^7\,{\rm g\,s^{-1}}$. Over 10^6 yr of sustained accretion at this rate, a typical white dwarf would accumulate 7×10^{18} g of calcium in its convective envelope; longer timescales are irrelevant because diffusion begins to compete with accretion. This quantity of calcium is able to account for a small minority of the observed envelope masses plotted in the upper panel of Figure 2; the average calcium mass is 10 times higher, with a few values 3 orders of magnitude greater. This calculation assumes 1) the highest accretion rate for dust grains within dense ISM regions, and 2) stars that currently retain their peak calcium abundances to within an order of magnitude. Hence, the calculation should *over predict* the amount of calcium polluting the stellar convection zones by one to a few orders of magnitude. Therefore, if this analysis is valid to within an order of magnitude, it is all but certain that the photospheric calcium in DZ stars cannot have interstellar origins.

The DAZ white dwarfs make this point even more striking. For these polluted, hydrogen atmosphere stars with thin convection zones and short metal diffusion times relative to the DZ stars, Koester & Wilken (2006) infer continuous and ongoing mass accretion rates based on a highly probable, current steady state balance between accretion and diffusion. The inferred DAZ accretion rates for Solar abundance matter, up to $2 \times 10^{11}\,{\rm g\,s^{-1}}$, are quite similar to the high rate assumed by Dupuis et al. (1993a) for the DZ stars. Yet no correlation is found between the implied DAZ accretion rates and the total space velocity of the stars as expected in the case of fluid accretion (Koester & Wilken 2006). Furthermore, there are no known regions of enhanced LISM density in the vicinity of the DAZ stars (Kilic & Redfield 2007; Koester & Wilken 2006; Zuckerman et al. 2003), and Table 3 reveals that accretion rates of $10^{11}\,{\rm g\,s^{-1}}$ are only even theoretically possible within relatively dense clouds, which are not seen. Lastly, there is firm evidence that the nearby DAZ G29-38 does not accrete matter at the fluid rate, but rather has an upper limit based on X-ray observations that is 25 times lower (Jura et al. 2009b).

There is no physical reason why helium and hydrogen atmosphere white dwarfs should become polluted via separate mechanisms; in fact, Occam's razor argues against a bimodal theory. The fact that some examples of both varieties of metal-contaminated stars are found with closely orbiting dust is testament to this fact (Farihi et al. 2009). In this regard, the only real difference between the DZ and DAZ stars is that the latter group is currently accreting from its immediate surroundings, while the former group carries their metallic scars long after a pollution event has ended (Koester 2009).

4 SPATIAL - KINEMATICAL ANALYSIS

4.1 Polluted White Dwarfs in the Local Bubble

While Koester & Wilken (2006) obtain capture rates up to 10^{11} g s^{-1} in the warm, ionized LISM within the Local Bubble which assumes fluid accretion is valid for heavy elements, there are still serious problems with this picture when applied to the DZ stars. The individually identified parcels of LISM span at most a few pc (Redfield & Linsky 2008), corresponding to several 10^4 yr of traversal by a typical DZ white dwarf. Such an encounter in a typical region of LISM with $\rho_\infty = 0.1\,\mathrm{cm}^{-3}$ (Redfield & Linsky 2000) leads to $\dot{M}_{\rm BH}$ rates of 10^8 g s^{-1}, and would provide only 10^{16} g of calcium pollution if accreting Solar abundance matter. While such modest an amount of metal can effectively pollute the relatively thin outer layers of DAZ stars, this paltry calcium mass requires 10 000 LISM encounters to account for the average calcium mass in the DZ star envelopes. Of course, this presumes fluid accretion is viable for heavy elements, which has been shown above to be physically implausible, thus making legion fluid infall episodes unlikely in the extreme. Therefore, it is safe to conclude that within the Local Bubble, ISM accretion is inconsistent with the phenomenon of DZ stars, which on average travel only 50 pc during a 10^6 yr metal sinking timescale.

4.2 ISM Accretion Above the Galactic Disk?

Prior to the SDSS, there were few (if any) cool ($T_{\rm eff} \leqslant 12\,000$ K) white dwarfs known beyond 200 pc (McCook & Sion 1999). Generally a hindrance for both magnitude limited as well as proper motion surveys, such distant cool degenerates would have $V > 18$ mag, while 100 km s^{-1} tangential speeds only yield $\mu \lesssim 100\,\mathrm{mas\,yr}^{-1}$. The DZ sample of Aannestad et al. (1993) was limited to within 50 pc of the Sun, but the SDSS DZ sample stretches out to 300 pc *above the disk of the Milky Way* (see Figure 1). While the single DZ outlier at $|z| > 400$ pc is likely to be a higher than average mass white dwarf (i.e. its photometric distance is overestimated), the sample as a whole contains 96 (66%) and 26 (18%) stars situated more than 100 and 200 pc above the plane of the Galaxy. This fact alone perhaps provides an insurmountable challenge to the ISM accretion hypothesis.

The scale height of molecular gas as measured by CO is 75 ± 25 pc (Dame & Thaddeus 1985), while that of neutral, atomic hydrogen is roughly 135 pc with substantial irregularities (Lockman et al. 1986). Taking 100 pc as a fiducial scale height for interstellar gas and dust, and assuming the entire sample of DZ stars obtained their metals from this medium requires the stars: 1) are currently traveling through or away from the Galactic mid-plane, and 2) have not traveled significantly further than around 18 pc above the gas and dust layer, on average. This distance constraint corresponds to a star traveling at the sample mean $|W| = 18\,\mathrm{km\,s}^{-1}$ speed (see Table 2) over a typical Myr diffusion timescale.

However, these requirements do not match the observations. First, more than half the sample (81 stars or 58%) currently sit more than 120 pc above the disk of the Galaxy. Second, and rather damningly, *nearly half of the sample is moving back into the disk rather than away.* The upper panel of Figure 5 reveals 67 polluted white dwarfs that are currently moving back toward the Galactic mid-plane. Many of these stars are among the most highly polluted in the sample, and many have $|z| \gtrsim 100$ pc. The middle panel of the same figure shows the height above the disk as a function of total space velocity; surprisingly some of the fastest stars are also high above the plane. These results strongly conflict with expectations from ISM accretion models.

In order to estimate how much time high $|z|$ DZ stars spend above the spiral arms and interwoven disk material, one can use the Solar motion as a first estimate. Depending on the Galactic model potential, and whether it includes dark disk matter, the Sun oscillates about $z = 0$ every 60 to 90 Myr (Matese et al. 1995; Bahcall & Bahcall 1985; Mihalas & Binney 1981), the former and latter values derived using models containing substantial and no dark disk matter, respectively. Kuijken & Gilmore (1989) provide $W_{\rm max}$ and $z_{\rm max}$ data for $100\,\mathrm{pc} \leqslant z \leqslant 2000$ pc based on a sample of K dwarfs toward the South Galactic Pole and a Galactic model which contains no dark disk component. Using a simple harmonic oscillator model, a period can be computed from these maximum heights and speeds for stars within several hundred pc of the disk. The period of a simple oscillator is

$$P_z = 2\pi\sqrt{\frac{K_z}{m}} \tag{10}$$

where

$$K_z = m\left(\frac{W_{\rm max}}{z_{\rm max}}\right)^2 \tag{11}$$

In reality, the period is a function of z due to the disk component of the Galaxy, which acts as a linear term in the vertical gravitational potential, while the spherical component (including the inferred dark halo) acts as a quadratic term, equivalent by itself to a harmonic potential (Bahcall et al. 1999). Using the above equations and the data of Kuijken & Gilmore (1989) for stars within 500 pc of the plane, the mean period is $P_z = 80 \pm 10$ Myr and compares favorably to rigorously derived values for the Sun. Taking $P_z = 80$ Myr, one can then use the same simple model to calculate the length of time a DZ star with current velocity W and height z has spent outside the 100 pc Galactic gas and dust layer.

The lower panel of Figure 5 plots a histogram of the outward- and inward- bound DZ white dwarfs which are currently at least 100 pc above the Galactic mid-plane. All 96 of these stars have spent more than 3 Myr in a region of space where the accretion of interstellar matter can be likely ruled out, 91 of these metal-polluted stars have been out of the Galactic disk for over 6 Myr. As can be seen by

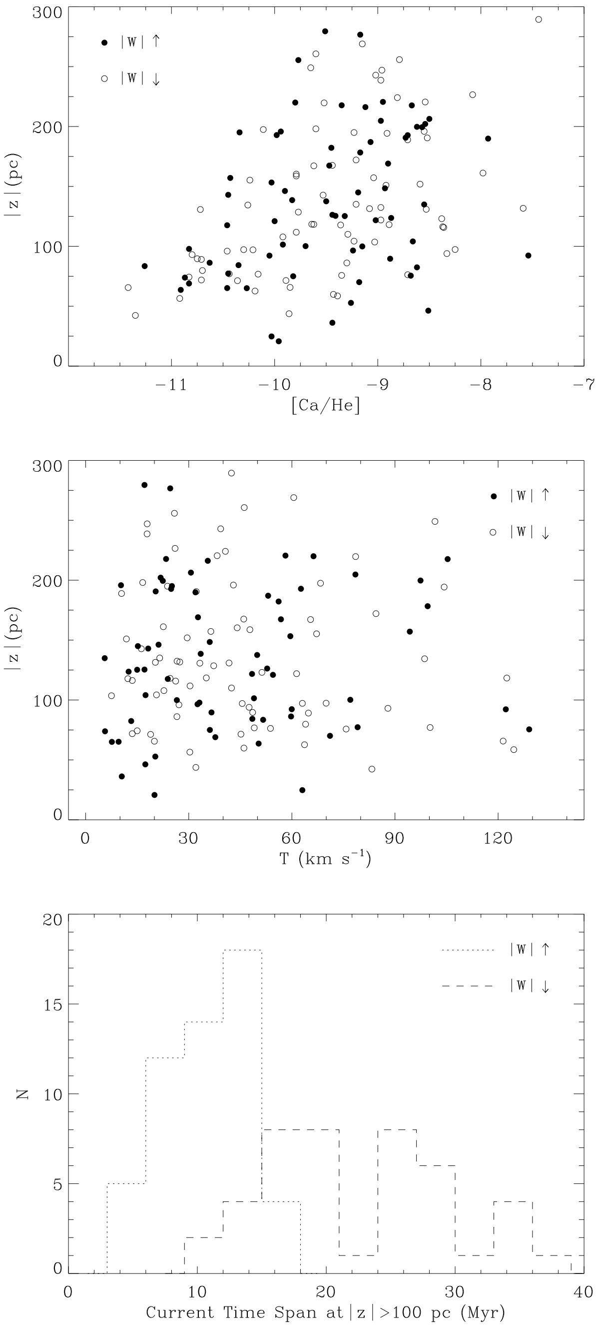

Figure 5. The upper panel reveals 67 DZ stars moving back toward the Galactic mid-plane, many among the most highly metal-polluted stars in the sample. The middle panel shows the total space velocity as a function of height above the Galactic disk, with many stars exhibiting high values along both axes. The lower panel is a histogram of Myr spent at $|z| > 100$ pc for the 96 DZ stars currently located in this region.

reviewing Figure 1, these high $|z|$ DZ stars are not anomalous in terms of their abundances, but rather mundane and truly representative of the sample at large. If anything these white dwarfs have higher abundances than the lower $|z|$ stars (but this is likely a bias resulting from spectroscopic calcium detection sensitivity).

If the majority of these DZ white dwarfs have traveled away from where they were polluted for a few to several diffusion timescales, the extant photospheric metals represent only a fraction of their peak abundances. This picture dramatically exacerbates the original problem of the metal origins in the following manner. Instead of accounting for $10^{22\pm2}$ g of total accreted metals, a viable theory must now account for nearly $10^{24\pm2}$ g – Ceres and Moon masses of heavy elements – for a sample which has traveled for 4 to 5 diffusion timescales in the absence of accretion. This possibility would greatly strengthen the need for efficient delivery of planetesimal-size masses of heavy elements, and combined with the hydrogen deficiency, is more rather than less challenging to explain with interstellar accretion. Hence this possibility is not considered further.

4.3 ISM Accretion At High Speed?

Throughout the preceding sections, a nominal $50\,\mathrm{km\,s^{-1}}$ tangential speed was used for relevant calculations; this value being somewhat friendly to ISM accretion models and also the mean among the 146 DZ stars in the sample. However, there are 13 stars with $v_{\rm tan} \geqslant 100\,\mathrm{km\,s^{-1}}$ (and total space velocities, $T > 100\,\mathrm{km\,s^{-1}}$ since their radial velocities are unknown and assumed to be zero), which would imply a decrease in the Table 3 fluid accretion rates by an order of magnitude. There appears to be no correlation between these speeds and the accreted calcium abundances in the DZ stars (see Figure 1), and hence there seems little or no chance that these stars have accreted in this manner. Koester & Wilken (2006) finds a similar lack of correlation among the known DAZ stars; a more striking statement given their necessary ongoing accretion.

While the dependence of geometrical accretion on velocity is milder by comparison, for ISM accretion scenarios it is reasonable to expect a mild correlation should exist between accreted mass and velocity, yet no such correlation is seen in Figures 1 or 3. In the middle panel of Figure 5, one would expect to find milder velocities necessary to capture more ISM material as stars move away from the Galactic gas and dust layer and into regions where the ISM is tenuous at best, yet this pattern is not observed.

5 THE SDSS DZ AND DC WHITE DWARFS COMPARED

If the ISM accretion hypothesis is correct, then the only difference between a DZ and a DC star is its recent (within a few Myr) spatial and kinematical history. That is, during that time a DZ star has recently exited a relatively *dense* patch of ISM, while a DC star has not (the continuous, warm-phase ISM accretion scenario forwarded by Koester & Wilken (2006) does not work for the DZ stars, as demonstrated above). Is this the correct picture?

There are a similar number of DZ and DC white dwarfs in the SDSS and a comparison of their model effective temperatures, $g - z$ colors (the longest baseline possible which is unaffected by calcium H and K absorption), Galactic heights, and tangential speeds is shown in Figure 6. There appear to be a few modest differences between the sample distributions; a small group of relatively lower temperatures,

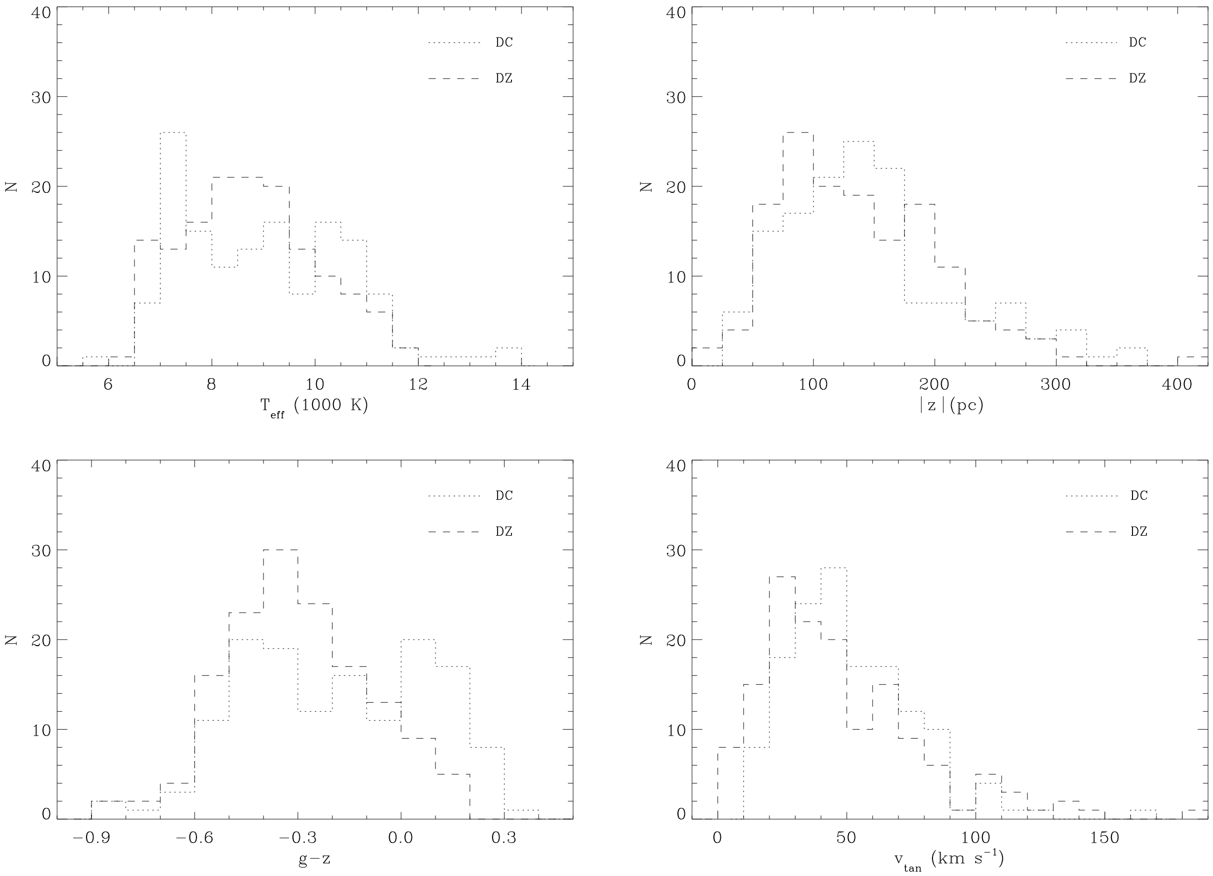

Figure 6. Effective temperature, $g-z$ color, Galactic height, and tangential speed histograms for the DZ and DC white dwarfs. For the most part, these two spectral classes appear to represent the same population of helium-rich white dwarfs.

and a flatter color distribution are found among the DC stars, while the $|z|$ and $v_{\rm tan}$ distributions are fairly similar. Table 2 demonstrates the two spectral classes have mean parameters which agree rather well despite the relatively large standard deviations; their average effective temperatures, distances, Galactic heights, and tangential speeds all agree to within 4% to 8%.

Figure 7 plots the *UVW* space velocities of the DZ and DC samples (assuming $v_{\rm rad} = 0$), supporting the idea they are both basically thin disk populations, each with several possible thick disk members. Table 2 shows the two groups share the same mean space velocities and velocity dispersions, the latter being the most important indicator of kinematical age (Jahreiß & Wielen 1997; Mihalas & Binney 1981). Together these analyses suggest DZ and DC white dwarfs belong to the same population of helium atmosphere, thin (and a few thick) disk stars.

5.1 Convergent and Divergent Pairs of DZ and DC White Dwarfs

Figure 8 projects the Galactic longitude and latitude of all the DZ and DC stars onto the plane of the sky. While it is true that the SDSS observes only certain areas of the sky, and hence one can a priori expect these two groups to occupy overlapping regions, the degree of overlap between the DZ and DC white dwarfs is total; there does not exist any region where DZ stars are found in higher concentrations than their DC counterparts. However, this type of projection is very dense on paper while the actual sky is rather vast, and it necessarily ignores the third dimension, namely the distance from the Sun. Therefore a pertinent question to ask is whether any of these stars are pc-scale neighbors. A search was conducted around each DZ and DC star for other sample stars within a $r = 10$ pc radius, and the results are listed in Table 4.

All together 18 pairs of stars were identified in this manner, three of which lie together within a 5 pc region of space. There are nine DZ-DC, 4 DZ-DZ, and 5 DC-DC pairs; exactly half the pairs are of mixed spectral type. Of the DZ-DC pairs, there are three where the total space velocities agree to within 12 km s^{-1}, pairs #1, 6, and 10. In the latter case, each space velocity component by itself agrees within 3 km s^{-1}(!). These three pairs of stars have traveled the last 10^6 yr in adjacent regions of interstellar space, yet each component star has evolved distinctly from its partner – one metal-polluted and the other not. Furthermore, there are two DZ-DZ pairs whose total space velocities differ by more than 100 km s^{-1}, thus implying their current spatial convergence is in contrast to their divergent interstellar history over the last 10^6 yr. Therefore, these two DZ-DZ pairs

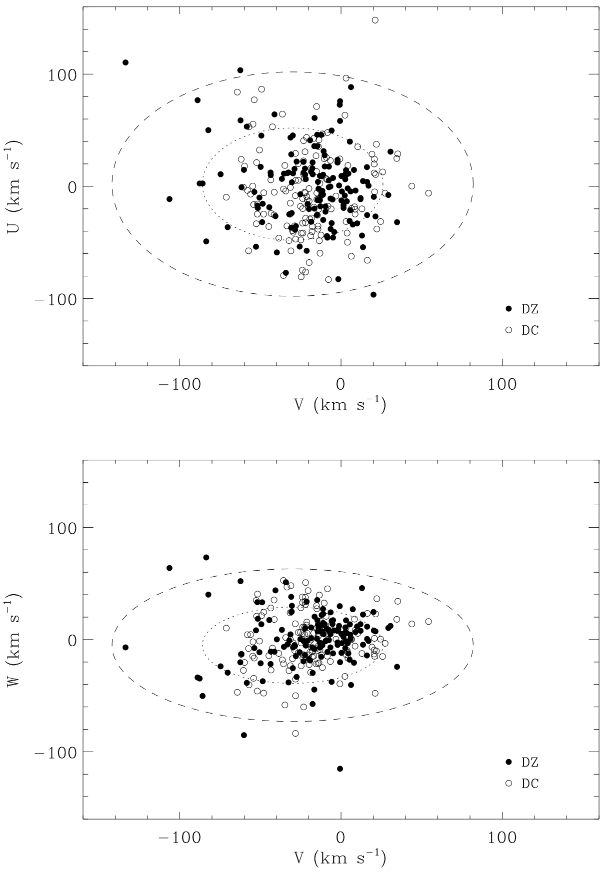

Figure 7. *UVW* space velocities for the DZ and DC white dwarfs calculated assuming $v_{\rm rad}$=0. The ellipses shown in the plots are the 1 and 2σ contours for old, metal-poor disk stars from Beers et al. (2000).

obtained their metals while traversing distinct rather than adjacent regions of the Galaxy.

Both the DZ-DC pairs with convergent spatial histories, as well as the DZ-DZ pairs with divergent orbital pasts are strong counterexamples to expectations for accretion within dense interstellar clouds of sizes several pc or larger. This is not surprising in the sense that such clouds do not exist within the Local Bubble, but again necessitates the existence of plentiful, smaller ISM patches to account for 1) many of the pairs in Table 4, and 2) the DAZ spectral class (Koester & Wilken 2006). As discussed above, the scenario of small (undetectable) cloud encounters may work for the DAZ stars, but not for the DZ class; it requires thousands of such encounters to accumulate the large mass of metals currently residing in their convection zones.

5.2 The Frequency of Metal-Free Counterparts to DZA Stars

A white dwarf accreting Solar ratio abundances at the high Eddington rate for 10^6 yr will obtain about 3×10^{21} g of hydrogen, and it is tempting to imagine the hydrogen masses in Figure 2 represent an accumulation of such encounters. Jura et al. (2009b) plots a similar figure but including hydrogen masses in warmer DBA white dwarfs from Voss et al. (2007). Generally speaking, the hydrogen envelope masses in DBA stars are one to a few orders of magnitude smaller than those in the DZA, making it plausible that as helium-rich stars cool and accrete ISM gas, the hydrogen accumulates.

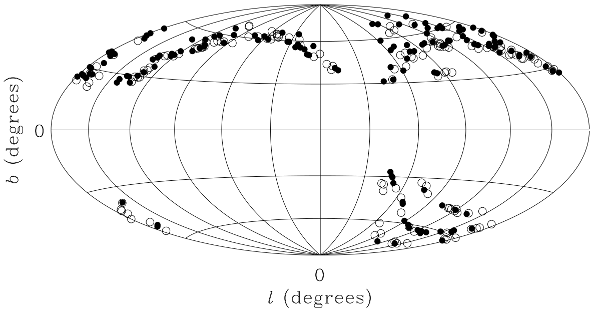

Figure 8. Projection of the DZ and DC Galactic coordinates.

If helium-rich stars gradually accumulate hydrogen from the ISM as they cool, there should exist a significant population of cool, helium-rich white dwarfs that reveal themselves as DA stars, which has not yet been observed (Zuckerman et al. 2003; Bergeron et al. 2001). Accreted hydrogen should perpetually float in a helium-rich star, while any metals eventually sink below detectability; this expectation is corroborated in high-resolution spectroscopy of DB stars, where the metal-free DBA outnumber the DBAZ stars 15:1 (Voss et al. 2007). While this ratio should decrease in the cooler DZA temperature range as diffusion timescales and atmospheric opacity favor a more frequent detection of calcium, the relative number helium-rich DA and DZA stars should remain larger than unity for all scenarios where metals and hydrogen have distinct origins. This arises because separate sources for hydrogen and metals, in helium atmosphere white dwarfs, imply independent probabilities, and being polluted by both will be the least probable. Therefore, if one assumes that metals result from accreted asteroids but under-abundant hydrogen in a cool, helium atmosphere is either 1) interstellar, 2) primordial, or 3) the result of dredge up and subsequent mixing, a larger than unity ratio of metal-free counterparts to the DZA stars is certain.

However, if the photospheric metals and hydrogen both have a circumstellar origin, and are semi-continuously delivered to the photosphere on relevant timescales, the ratio of helium-rich DA to DZA stars can potentially be less than unity. There are three mixed helium-hydrogen atmosphere stars among the 152 cool white dwarfs thoroughly studied and modeled by Bergeron et al. (2001); two are DZA stars(!), while the third has atmospheric carbon (where dredge up of interior carbon and helium in a previously hydrogen-rich atmosphere is a possibility). While this ratio of 1:2 (or 0:2) results from small number statistics, it may nonetheless be telling. The significant populations of DC and DZ stars, coupled with the relative lack of cool, helium-rich DA white dwarfs supports a circumstellar origin for hydrogen in DZA stars.

Furthermore, Occam's razor favors a single mechanism that can account for all the data simultaneously; hydrogen delivered together with heavy elements in water-rich minor planets is one such possibility. Jura et al. (2009b)

Table 4. Pairs within 10 pc of one another

Pair	Star_1	Star_2	SpT_1	SpT_2	Δr (pc)	ΔU (km s^{-1})	ΔV (km s^{-1})	ΔW (km s^{-1})
1	J020132.24−003932.0	J015604.19−010029.3	DZ	DC	3.4	6.1	4.3	1.8
2	J084828.00+521422.5	J083736.58+542758.3	DZ	DC	5.4	49.3	57.6	42.9
3	J084828.00+521422.5	J085133.95+542601.2	DZ	DC	5.2	20.5	14.2	22.1
4	J084828.00+521422.5	J090729.10+513805.6	DZ	DC	9.2	19.6	7.1	20.6
5	J093423.17+082225.3	J093819.84+071151.6	DZ	DC	3.1	7.8	21.8	13.1
6	J104915.06−000706.2	J105632.20−001041.3	DZ	DC	8.9	9.3	7.3	2.4
7	J123455.96−033047.1	J124006.36−003700.9	DZ	DZ	7.6	2.1	21.3	12.7
8	J124006.36−003700.9	J124333.86+031737.1	DZ	DC	8.4	35.3	0.6	7.4
9	J131336.96+573800.5	J131750.20+600532.9	DZ	DC	6.7	9.1	115.1	55.6
10	J135137.07+613607.0	J135137.07+613607.0	DZ	DC	6.0	2.4	1.5	1.6
11	J144022.52−023222.2	J144516.24−020849.6	DZ	DZ	6.4	69.6	55.8	47.2
12	J210733.93−005557.7	J212424.69−011452.5	DZ	DZ	9.2	80.2	22.2	57.6
13	J223222.32+010920.7	J223841.05+010150.3	DZ	DZ	3.8	4.3	32.1	28.7
14	J021546.95−073226.8	J022147.29−084236.1	DC	DC	6.2	7.1	100.0	9.5
15	J033939.67+001539.8	J034401.34−001221.0	DC	DC	8.6	23.9	22.1	29.3
16	J083736.58+542758.3	J085133.95+542601.2	DC	DC	5.6	28.8	43.4	20.9
17	J104718.30+000718.3	J111007.61+011041.4	DC	DC	9.6	116.8	17.0	8.3
18	J130526.15+001250.8	J131056.92−002451.9	DC	DC	8.1	124.7	35.0	31.1

offer this hypothesis to explain, with a single pollution event, the collective facts available on the spectacularly metal-enriched, mixed helium-hydrogen atmosphere white dwarf GD 362. This disk-polluted, helium-rich star has an anomalously high hydrogen abundance at $[\mathrm{H/He}] = -1.1$ (Zuckerman et al. 2007), so much that it was originally classified as DAZ (Gianninas et al. 2004). GD 16 is a similar case with significant atmospheric hydrogen (Koester et al. 2005b) and a dust disk polluting its helium-dominated atmosphere (Farihi et al. 2009), while the two remaining helium-rich white dwarfs with disks (GD 40 and Ton 345) have little or no hydrogen (Jura et al. 2009b). Therefore, the pattern of hydrogen abundances in DZ stars is likely a reflection of the diversity of water content in extrasolar planetesimals.

6 OUTSTANDING ISSUES

Owing to the fact that radial velocities are not reliably measurable from the calcium lines in the SDSS spectra of the DZ stars, some of the derived kinematical quantities are modestly uncertain. Fortunately, the galactic latitudes of the 146 stars are bound within $25^\circ < |b| < 75^\circ$, and potential biases are mild at worst. For example, although the calculation of W velocity here is missing the third dimensional ingredient, which could potentially alter its sign (and hence direction), a non-zero radial velocity will tend to increase their speeds in any given direction $[T^2 = U^2 + V^2 + W^2 = {v_{\rm tan}}^2 + {v_{\rm rad}}^2]$. Moreover, the focus of the study has been statistical in nature and the global properties of the sample are unlikely to change (Pauli et al. 2003; Silvestri et al. 2002)

GAIA will eventually obtain distances to, and excellent proper motions for, most if not all the DZ and DC white dwarfs, the latter stars being immune to radial velocity measurements by nature (until more powerful instruments resolve any potential lines in their spectra). Empirical distance determinations will remove any bias introduced with the assumption of $\log g = 8.0$, but again this is unlikely to be problematic from a statistical point of view (Kepler et al. 2007).

Perhaps more important is the current understanding of how interstellar accretion occurs; this ignorance alone can sweep up many uncertainties, just as passing stars may sweep up ISM, but this situation is not ideal, and empirical constraints are superior. Although the propeller mechanism hypothesis may be currently broken, or minimally in need of repair (Friedrich et al. 2004), this does not rule out the *logical* possibility of preferential accretion for heavy elements (grains) versus gas while a star traverses a patch of ISM. However, there are two worthwhile considerations for any such hypothesis.

First, based on reasonable physics in the absence of propeller-like deterrents, the infall of gas onto a star via the ISM should proceed at a rate much higher than the analogous accretion of grains (§3.4). Two additional factors should further increase the accreted volatile-to-refractory element ratio: 1) the intrinsic gas-to-dust ratio in the ISM is around 100:1, and 2) interstellar grain species should be separated further in the accretion process owing to varying evaporation temperatures (Alcock & Illarionov 1980). At present there does not exist a large number of cool white dwarf spectra exhibiting sufficient elements to confidently evaluate the volatile-to-refractory element ratios. Obtaining such a database would be highly valuable.

Second, there is a class of main-sequence star which is thought to accrete ISM and become polluted in the *opposite* sense to contaminated white dwarfs. The λ Bootis stars are a class of late B to early F stars that show nearly Solar abundances of light elements but are deficient in metals (Baschek & Slettebak 1988). It has been suggested that their abundance ratios mimic the metal-depleted pattern of interstellar gas (Venn & Lambert 1990), and that accretion-diffusion of this volatile-enriched gas is consistent with the observations (Kamp & Paunzen 2002; Charbonneau 1991). Since λ Bootis stars are generally A-type dwarfs where convection has become important, they should share some basic characteristics with cool white dwarfs in the appropriate effective temperature range. If the λ Bootis stars are polluted by interstellar, metal-poor gas, then any ISM accretion theory for white dwarfs should be able to account for both classes of stars, and explain specifically why preferential accretion would favor heavy elements in the case of white dwarfs, contrary to reasonable physical expectations.

7 CONCLUSIONS

The SDSS currently contains a large number of cool, metal-polluted, helium atmosphere white dwarfs over a relatively large volume of the local Galaxy. These DZ stars appear to be, on average, atmospherically, spatially, and kinematically similar to a comparable number of DC white dwarfs from the same catalog, at least superficially. A search for correlations between calcium and hydrogen abundances, spatial and kinematical properties among the DZ stars yields negative results, excepting a tendency for increased hydrogen mass with cooling age in DZA stars. Specifically, the metal abundances of 146 DZ stars shows no connection with speed relative to the LSR, nor with height above the Galactic disk.

The super-solar [Ca/H] ratios and lower limits are as expected for the DZ spectral class, but nonetheless difficult to understand as accretion of matter which is over 97% hydrogen and helium. The substantial fraction of the DZ sample which sits at $|z| > 100\,\mathrm{pc}$ is difficult to reconcile with accretion of ISM, perhaps impossible. The total space velocities of these high $|z|$ stars are no slower than their counterparts within the Galactic gas and dust layer, and hence no more amenable to accretion of rogue ISM patches, which are unlikely to exist in any case. These 96 stars have spent 3 to 40 Myr above the 100 pc half-width scale height of ISM, with 91 spending at least 6 Myr, the latter time period sufficient to drive their metal abundances down by a factor 400.

The calcium masses currently residing in the convective regions of the DZ stars are near 10^{20} g on average. If one assumes the calcium represents 1.6% of the total mass (equivalent to the bulk Earth; Allègre et al. 1995) of heavy elements in the stellar envelope, then a typical DZ star contains a mass equivalent to a 150 km asteroid. This is the *minimum* mass of accreted heavy elements. If a large percentage of DZ stars have retained metals from a past encounter within a few to several Myr diffusion timescales, then the present envelope masses of heavy elements represent only a fraction of the accreted masses and invoking total captured masses as large as the Moon.

Simply taking the 146 DZ stars out of 4193 DR4 white dwarfs with $T_{\rm eff} < 12\,000\,\mathrm{K}$, one can say that at least 3.5% of white dwarfs appear to be polluted by circumstellar matter, the remains of rocky planetary systems. This translates directly into a similar lower limit for the formation of terrestrial planets at the main-sequence progenitors of white dwarfs, primarily A- and F-type stars of intermediate mass. While this fraction is likely to be significantly higher (Zuckerman et al. 2003), it is difficult to quantify without a commensurate examination of all the cool SDSS white dwarfs, which is beyond the scope of this paper. The appearance of hydrogen in DZA stars suggests a common origin for both heavy elements and hydrogen, and indicates DZA star pollution by water-rich minor planets may be semi-continuous on Myr timescales. This picture can be tested by searching for sensitive features of oxygen absorption in hydrogen- and metal-polluted white dwarfs.

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